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TRACE FOSSILS AND DEPOSITIONAL ENVIRONMENT OF FOUR CLASTIC UNITS, UPPER PENNSYLVANIAN MEGACYCLOTHERMS, NORTHEAST KANSAS

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ABSTRACT

Trace fossils were collected and studied from four clastic units (Rock Lake Shale, South Bend Limestone, Stull Shale, and Tecumseh Shale) within three different megacyclothems in northeast Kansas. Forty-one different types of trace fossils are recognized. Thirty are identified as separate ichnogenera, and three of them are new ones. Eleven less distinct forms are also described. The depositional environment for each of these four clastic units is interpreted with the aid of their trace fossils.

The Rock Lake Shale is a medium to light gray shale. Trace fossils are preserved on thin beds of lenticular siltstone or fine-grained sandstone, which are interbedded with clay. *Planolites*, *Asteriacites*, *Lockeia*, *Cochlichnus*, *Didymaulichnus*, *Isopodichnus*, *Rusophycus* and other arthropod traces, *Curvolithus*, *Conostichus*, *Microspherichnus* Hakes, *ichnogen. nov.*, *Chevronichnus* Hakes, *ichnogen. nov.*, *Tomaculum*, *Lingulichnus* Hakes, *ichnogen. nov.*, and resting impressions are the most common trace fossils. Body fossils are rare to absent. The South Bend Limestone overlies the Rock Lake Shale. The lower part of this limestone is a medium gray, fine-grained calcareous sandstone. The most abundant trace fossils are: *Arenicolites*, *Diplocraterion*, *Margaritichnus*, *Chondrites*, *Planolites*, and *Rhizocoralium*. Common body fossils are *Orthomyalina* and *Aviculopecten*. Study of the ichnofauna from these two units indicates that marginal marine (? lagoonal) conditions existed during deposition of the Rock Lake Shale. Subsequent deposition of the South Bend Limestone (its lower clastic half) is interpreted to have occurred in a more normal marine environment.

Trace fossils are common in the lower part of the Stull Shale. Lithologies are thin-bedded, lenticular sandstone interbedded with clay. These sediments are also flaser and wavy bedded. Common trace fossils are *Asteriacites*, *Teichichnus*, *Planolites*, *Didymaulichnus*, and gastropod trails. Channels occur near the top of the unit with a coal above them. The Stull Shale is interpreted to have been deposited in a near-shore, shallow water environment, which underwent episodes of rapid sedimentation.

A local transgression can be observed within the Tecumseh Shale by the study of trace fossils. In the lower part of the unit, *Planolites*, *Lockeia*, *Aulichnites*, and gastropod trails are common. These trace fossils are interpreted to represent shallow water, marine conditions. In the upper part of the unit, a change in the ichnofauna is readily visible. The appearance of *Diplocraterion*, *Arenicolites*, *Tigillites*, *Nereites*, *Chondrites*, *Neonereites biserialis*, and curved burrows suggests that marine conditions were less restricted (i.e., increased water agitation) than in the lower part. No coal unit was found in the Tecumseh Shale, and all trace fossils were preserved in thin-bedded sandstone.

Key words: Trace fossils, paleoecology, cyclic sedimentation, Upper Pennsylvanian, Kansas.

INTRODUCTION

The concepts of cyclic sedimentation have dominated geologic thought with regard to deposition of Upper Pennsylvanian strata in Kansas (Moore, 1936, 1966). It has been generally thought that fossiliferous limestone units were deposited during periods of marine transgression and that interbedded gray shale units were deposited during nonmarine or intermediate conditions. Previous investigations have dealt almost exclusively with the limestone units, and there is little doubt that they were deposited under marine conditions (Moore, 1966; Cocke, 1969; Toomey, 1969a,b, 1972, 1974; Heckel, 1972; von Bitter, 1972). Work has been done on the black shales (Evans, 1968; von Bitter, 1972; Heckel & Baesemann, 1975), but generally the remaining "gray shales," which sandwich the limestone units and with which this investigation is concerned, have been ignored.

There is good reason that the gray shales have not received closer inspection. They are commonly devoid of body fossils and where fossils have been found, the

faunas are not well developed and are poorly preserved. Sedimentologically, the gray shales are typically structureless and may possess the highly friable texture characteristic of an underclay. Occasionally, this monotony is broken by some bedding features, local development of siltstone and sandstone lenses, and occasional thin beds of coal.

The common absence of body fossils and the presence of coal have led to the general conclusion that the gray shales were deposited in nonmarine environments or in environments intermediate between nonmarine and marine (Moore, 1966; Heckel, 1972). A situation therefore existed in which paleoenvironmental interpretations were drawn on the basis of lithologic associations and the absence of evidence for marine conditions.

Many of these gray shale units contain abundant trace fossil assemblages, which prove to be useful tools for the interpretation of depositional environments.

PURPOSE

It is the purpose of this investigation 1) to study the trace fossil assemblages from four units (South Bend Limestone and Rock Lake, Stull, and Tecumseh Shales) within the Upper Pennsylvanian megacyclothems in eastern Kansas (Fig. 1, 2), 2) to attempt to interpret the depositional environments of each unit by the study of the trace fossils found there, and 3) to compare these results with the traditional concept of cyclic sedimentation proposed for these units in Kansas (Moore, 1936, 1950, 1966).

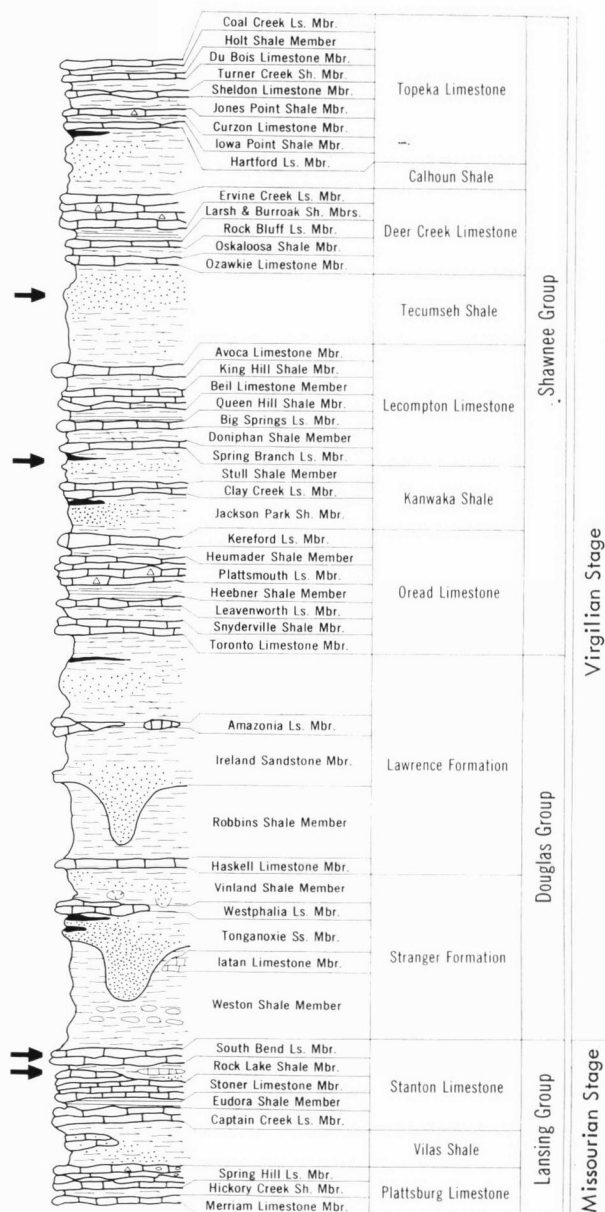
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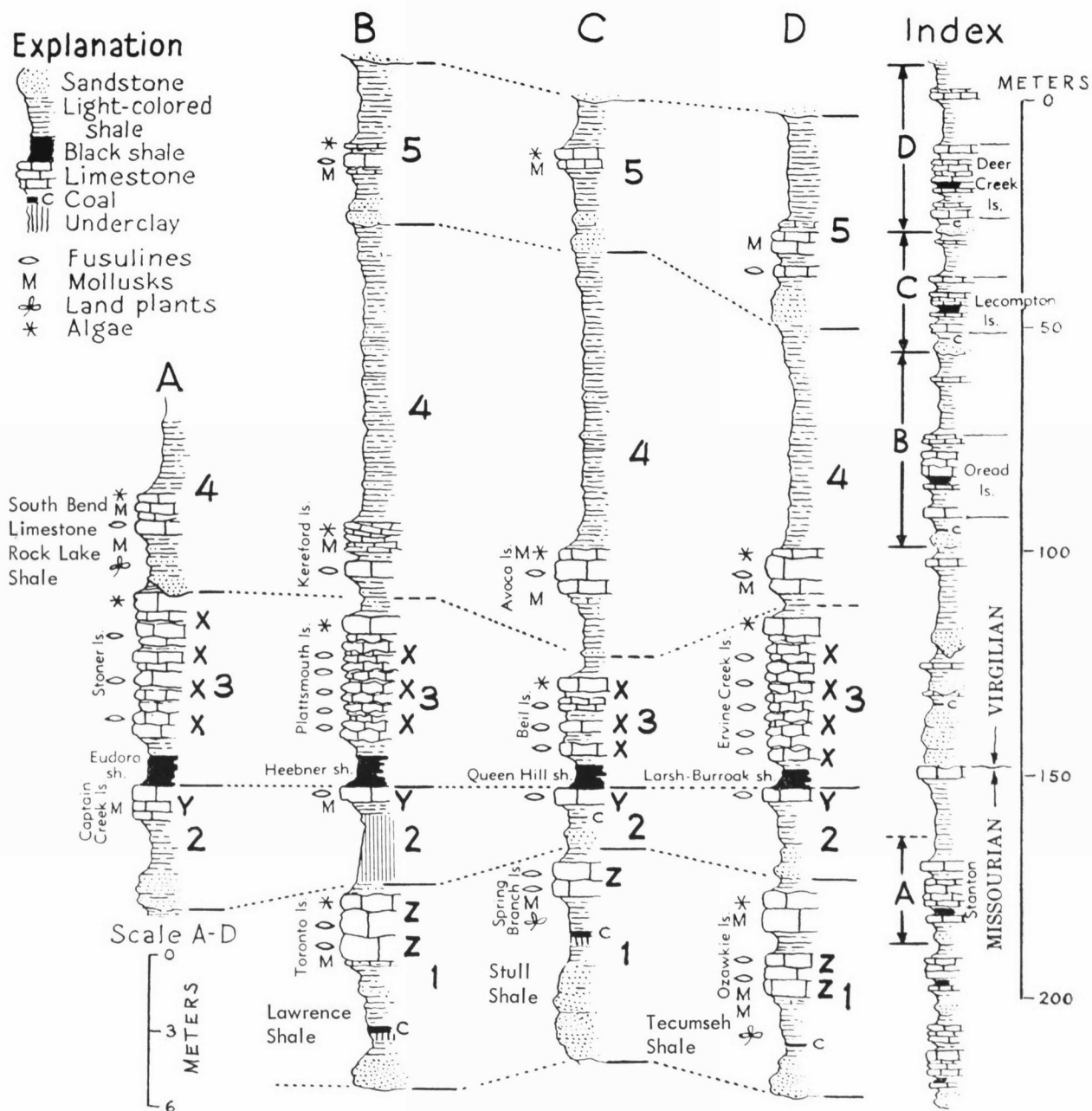
FIG. 1. Stratigraphic positions of four Upper Pennsylvanian units studied in this investigation. Units designated by arrows (from Zeller, 1968).



PREVIOUS WORK

Very little work has been done on trace fossils in the Upper Pennsylvanian cyclothems of Kansas. Moore & Merriam (1965, p. 13) pointed out the existence of numerous "tracks, trails, and burrows" in the Vilas Shale and Rock Lake Shale (Loc. 4), but did not describe them. Moore (1966, p. 293) mentioned the presence of tetrapod tracks in Pennsylvanian strata in Kansas but concluded that their distribution was too sporadic to determine their relation to cyclothems. Bandel (1967a) studied the

ichnofauna of the South Bend Limestone (Rock Lake Shale Loc. 5) and interpreted the unit to have been deposited in Seilacher's (1967) *Cruziana* facies. Limulid and isopod trails are also known from the Tonganoxie Sandstone in Franklin County (Bandel, 1967b). The depositional environment of the Lawrence Shale (Fig. 2) has been interpreted by the study of trace fossils (Hakes, 1973, 1974).



X- Light gray, wavy thin beds Y- Blue, dense, vertical-jointed even bed
Z- Yellow-brown, ferruginous, massive beds

Cyclothems of each megacyclothem are numbered in upward order

FIG. 2. Stratigraphic positions of Rock Lake Shale, South Bend Limestone, Stull Shale, and Tecumseh Shale within their respective megacyclothems (after Moore, 1950).

PALEOGEOGRAPHIC SETTING

During the Late Pennsylvanian, vast epicontinental seas covered the midcontinent of the United States. In the southwest, Arizona and New Mexico received almost entirely marine sedimentation, while in Kansas, the sediments are 40 to 70 percent marine. Marine sedimentation decreased toward the east so that in West Virginia predominantly nonmarine sequences are found (Wanless, 1950). In general, Upper Pennsylvanian strata across the state of Kansas consist of carbonate sequences to the west, interfingering with clastic facies in the east (Wanless, 1950; Rascoe, 1962).

Sediments of Late Pennsylvanian age that now crop out in northeastern Kansas were deposited primarily in shallow water environments (Heckel, 1972). The paleogeography of this and neighboring areas has been discussed by Moore (1929; 1936; 1966), Branson (1962a), Merriam (1963), Ham & Wilson (1967), Toomey (1969a), and Troell (1969). Late Pennsylvanian structural elements controlling deposition in eastern and northeastern Kansas were the Forest City Basin, Nemaha Structural Belt or Nemaha Anticline, and the Bourbon Arch (Fig. 3).

The Forest City Basin was situated in Iowa, Missouri, and Nebraska and only its extreme southwestern part extended into northeastern Kansas. It is not known whether the Forest City Basin was connected with the Eastern Interior Basin to the east during Late Pennsylvanian time (Branson, 1962a, fig. 1; Toomey, 1969a). The Forest City Basin was separated from the Cherokee Basin to the south by an east-west trending structural element, the Bourbon Arch. To the west, the Nemaha Structural Belt separated the Salina Basin in the north and the Sedgwick Basin in the south from the Forest City and Cherokee Basins, respectively. Both the Nemaha Structural Belt and the Bourbon Arch are overlain by Penn-

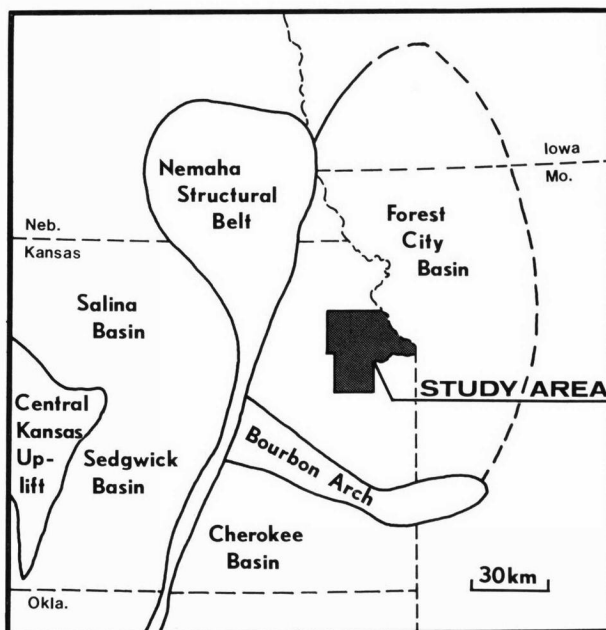


FIG. 3. Structural elements that influenced deposition within the study area during Pennsylvanian time (after Branson, 1962a; Merriam, 1963).

sylvanian sediments of character similar to those found within the Forest City Basin.

It has been long thought that the source area for most clastic sediments was to the south or southeast (Moore, 1931, p. 255). However, more recent work has demonstrated source areas for clastic sedimentation situated to the north, northwest, and northeast (Mudge, 1956, p. 675; Wanless *et al.*, 1970; Heckel, 1972, fig. 12).

STRATIGRAPHIC DESCRIPTIONS

Upper Pennsylvanian strata in northeastern Kansas are characterized by the cyclic repetition of shale and fossiliferous limestone units (Fig. 1). Their outcrop pattern is ribbonlike and strikes northeast across the state. The dip is less than five degrees to the west. Locations and detailed descriptions of the outcrops studied in this investigation are listed in the Appendix.

ROCK LAKE SHALE AND SOUTH BEND LIMESTONE

The stratigraphic position of the Rock Lake Shale and South Bend Limestone is shown in Figure 1. The Rock

Lake Shale and South Bend Limestone (in particular its lower part) are considered together here because they were studied together as a unit in the field (Fig. 4, 5).

Rock Lake Shale.—In eastern Kansas, the Rock Lake Shale is a gray to olive-gray, argillaceous to sandy shale, commonly less than one meter to over four meters in thickness. Locally it contains a thin black shale or thin coal overlain by a thin, laminated gray limestone (Zeller, 1968, p. 33). In Leavenworth, Wyandotte, and Douglas Counties, the Rock Lake Shale is a medium gray, clayey shale with a distinct bed of lenticular siltstone lenses that disappears to the south (Fig. 4). To the north in Nebraska, the Rock Lake grades into a reddish-brown shale

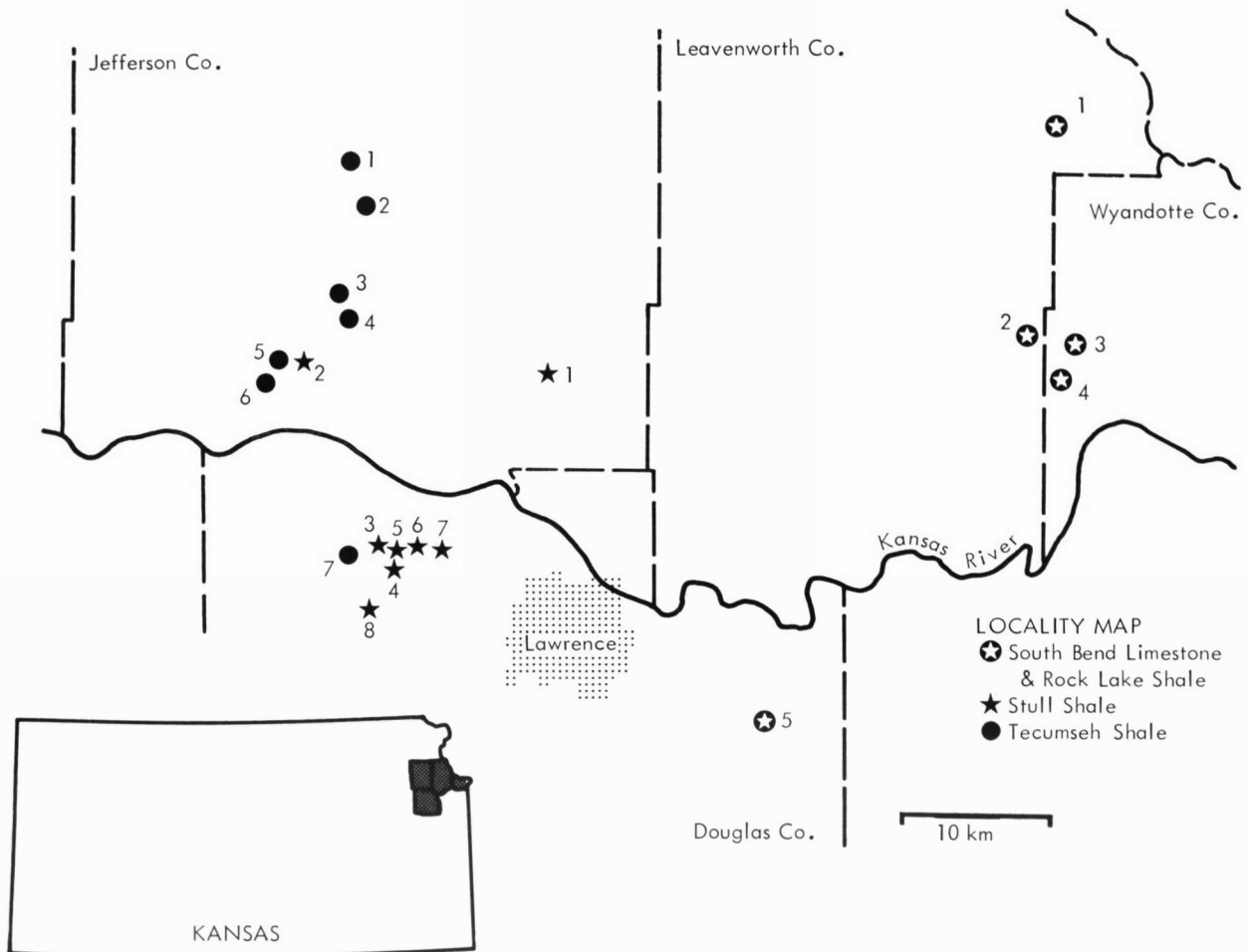


FIG. 4. Map of localities for Rock Lake Shale, South Bend Limestone, Stull Shale, and Tecumseh Shale.

(Russell, 1972). South of the study area, in Franklin County, the Rock Lake Shale is characterized by lithologic variability. Units of shaly limestones, containing a molluscan-brachiopod fauna, overlain by either a gray-green, clayey shale or by a brachiopod-bearing, calcareous shale, can be found locally. The lower contact with the Stoner Limestone is commonly brecciated (Ball *et al.*, 1963). An abundant plant and molluscan assemblage has been described from the Rock Lake Shale near Garnett, Anderson County, Kansas (Moore *et al.*, 1936). An insect (Carpenter, 1940) and vertebrate fauna (Peabody, 1952, 1957, 1958) are also known from the same locality.

South Bend Limestone.—The South Bend Limestone is between 0.3 and 1.8 meters thick in eastern Kansas and can be divided into two members. The upper unit is a medium- to thick-bedded, dense, fine-grained, medium to dark gray or bluish gray, fossiliferous limestone. This limestone weathers yellowish gray to yellowish brown.

The bottom member is sandy and conglomeratic (Zeller, 1968, p. 34). South of the study area, in Franklin County, the South Bend is discontinuous and, where present, its arenaceous lower part easily distinguishes it from the Rock Lake Shale (Ball *et al.*, 1963, p. 22).

[The boundary between the Rock Lake Shale and the South Bend Limestone, as used here, is the same as that considered by Moore & Merriam (1965, p. 13) and Heckel & Baesemann (1975). Bandel (1967a) used O'Connor's (1960, 1963) correlations in his investigation of trace fossils in the "Rock Lake Shale" at Killough Quarry near Eudora, Kansas (Rock Lake Shale Locality 5). In the stratigraphical scheme adopted here, Bandel's material belongs in the South Bend Limestone, not the Rock Lake Shale.]

The Rock Lake Shale and South Bend Limestone are not continuous within the study area because they have been partially or totally eroded and the erosion channels filled in by the Tonganoxie Sandstone, a channel sand (Lins, 1950, fig. 1, 3).

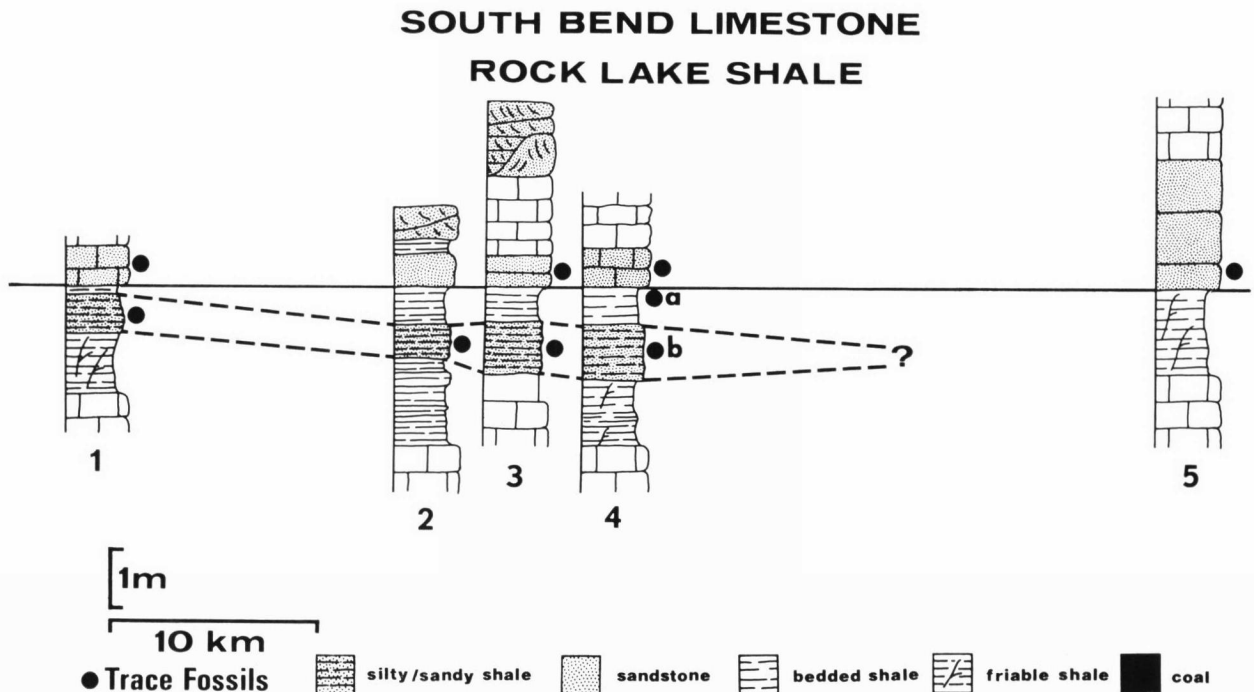


Fig. 5. Stratigraphic cross section of Rock Lake Shale (below solid line) and South Bend Limestone (above solid line). Cross-bedded sandstone is Tonganoxie Sandstone. [Dashed lines show lateral extent of siltstone unit containing trace fossils. Two different trace fossil horizons at the same locality designated by *a* and *b*. Refer to Tables 2 & 3. Geographic location of sections in Fig. 4.]

STULL SHALE MEMBER

The stratigraphic position of the Stull Shale is shown in Figure 1. In northeastern Kansas, a dark blue to bluish-gray limestone, the Clay Creek Limestone, stratigraphically separates the Stull Shale Member from the lower, Jackson Park Shale Member of the Kanwaka Shale. This limestone is absent in southeastern Kansas. Throughout eastern Kansas, the Stull Shale is from 8 to 15 meters thick (Zeller, 1968, p. 36). In Franklin County, the Stull Shale is apparently continuous. It is a tan, silty to clayey shale, locally sandy, and lacks megafossils except for occasional brachiopods and bryozoans in the upper two meters (Ball *et al.*, 1963, p. 36). The Stull Shale has been described in Douglas County to contain one or more thin coal beds and a sparse molluscan fauna, found south of the Wakarusa River (O'Connor, 1960, p. 42). Farther north in Shawnee County, Johnson & Adkison (1967) considered the deposition of the Stull Shale to be predominantly nonmarine with a return to marine conditions prior to deposition of the overlying Spring Branch Limestone Member of the Leocompton Limestone.

In the present investigation, the Stull Shale was studied in Jefferson and Douglas Counties (Fig. 4). In the north, the Stull commonly displays a coal unit, about 0.5 meters thick, one meter or so below the Spring

Branch Limestone. This coal unit may be represented by two or three thinner coal beds in some areas (Fig. 6). Within the study area, the Stull Shale may be characterized as a dark gray, clayey shale containing numerous beds of sandstone unevenly dispersed both horizontally and vertically. Much of the sandstone is thin-bedded, locally containing abundant mica flakes and plant debris. The sandstone content of the Stull Shale decreases south of Douglas County. In some areas, wavy, lenticular, and flaser bedding is present and reversal of very small scale cross bedding is occasionally found.

Soft sediment deformation is relatively common where the Stull Shale contains more thickly bedded sandstone (Fig. 7). Deformation may destroy original sedimentary structures within these sandstone beds. In other places thin-bedded sandstone layers, a few centimeters thick, are slightly deformed and discontinuous. It is not uncommon to find an outcrop in which one half is composed of thin, alternating beds of sandstone and clay and the other half is a more massive sandstone that has been deformed by penecontemporaneous, soft sediment deformation. Therefore, a great deal of information has been lost because these sands were deposited upon structurally incompetent muds (Dzulynski & Smith, 1963; Kuenen, 1965). Some of the better preserved sandstone

STULL SHALE

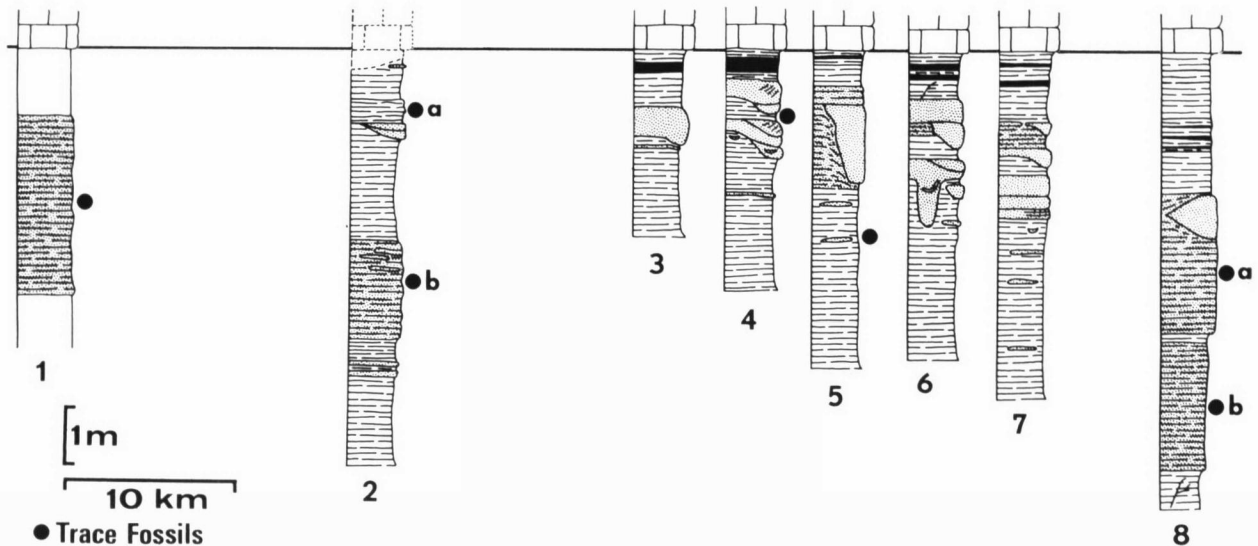


FIG. 6. Stratigraphic cross section of Stull Shale (below solid line). [Two different trace fossil horizons at the same locality designated by *a* and *b*. Refer to Table 4. Geographic location of sections in Fig. 4. For lithologic symbols see Fig. 5.]

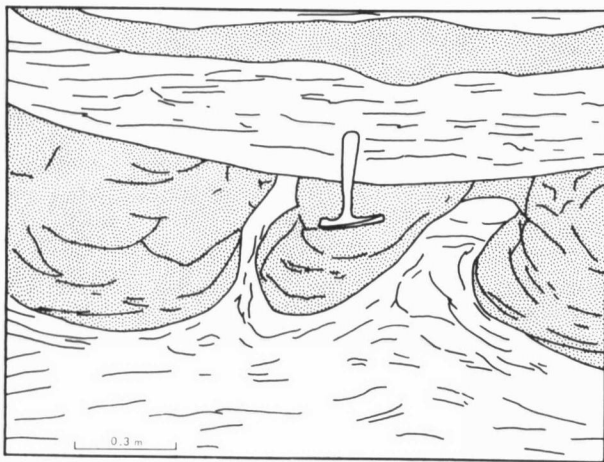


FIG. 7. Soft sediment deformation within Stull Shale with subsequent truncation. Drawn from a photograph.

bodies are lenticular with relatively flat tops and curved bases. These units rarely display poorly developed planar cross stratification with dips of about 20 degrees (Fig. 8). Commonly cross-bed sets are 10 to 20 cm thick. Many of these sandstone bodies are local, and it is difficult to correlate them within or between outcrops.

TECUMSEH SHALE

The stratigraphic position of the Tecumseh Shale is

shown in Figure 1. The Tecumseh Shale is a bluish-gray, clayey and sandy shale that crops out from southern Kansas northward into Nebraska where the Ost Limestone is present near the top of the unit. The thickness of the shale increases from 4 meters in the south to approximately 16 meters in northeastern Kansas. The formation has not been formally divided into members (Zeller, 1968, p. 37).

In Douglas County, the Tecumseh Shale commonly contains plant fragments. Marine fossils are rare to

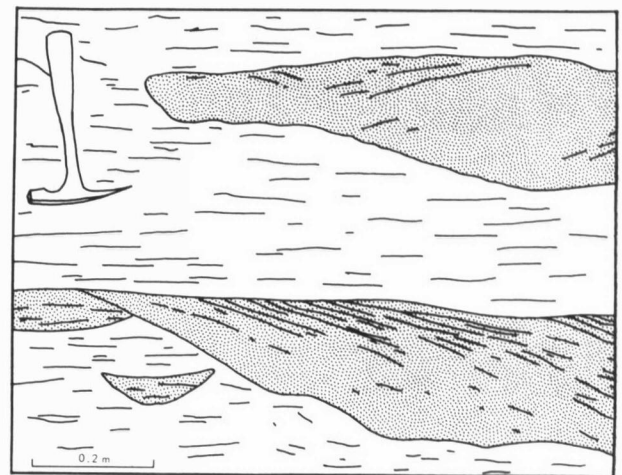


FIG. 8. Cross-bedded lens in Stull Shale (in lower half of figure). Drawn from a photograph.

absent in most exposures. Where present, they are found only within the uppermost meter of the shale, below the Deer Creek Limestone (O'Connor, 1960, p. 45). In Shawnee County, west of Jefferson County, Johnson & Adkison (1967) considered the base of the Tecumseh Shale to represent a regressing marine environment. According to these authors, most deposition during Tecumseh time was continental and transgressive conditions occurred just before deposition of the overlying limestone.

The Tecumseh Shale was studied in Douglas and Jefferson Counties (Fig. 4). Within this area, the unit may be characterized as a gray, clayey shale containing

distinct beds of sandstone and siltstone from approximately several centimeters to about a meter thick (Fig. 9). The sandstone within the lower half of the unit varies from gray to yellowish brown in color. Near the top of the Tecumseh Shale, the sandstone beds display small scale cross bedding and are occasionally wave rippled. These sandstone beds are continuous across an outcrop, but correlation between outcrops is difficult (Fig. 9). Many of the characteristic sandstone units pinch and swell apparently in an irregular fashion between outcrops. These beds disappear to the south in Osage County where the sediments are dominantly clays.

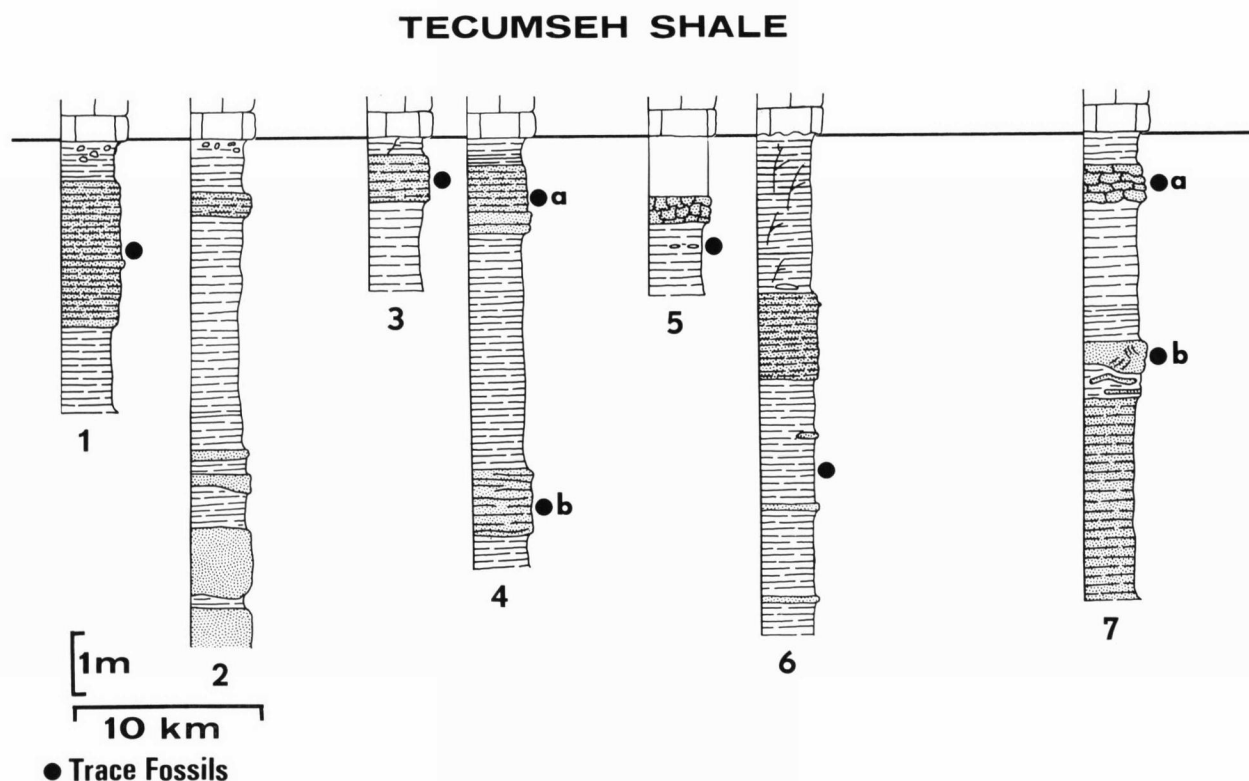


FIG. 9. Stratigraphic cross section of Tecumseh Shale (below solid line). [Two different trace fossil horizons at the same locality designated by *a* and *b*. Refer to Table 5. Geographic location of section in Fig. 4. For lithologic symbols see Fig. 5.]

DISCUSSION

BATHYMETRY OF TRACE FOSSILS

Seilacher (1967) divided characteristic trace fossil assemblages into six distinct bathymetric zones or ichnofacies. The benthonic environments and characteristic trace fossil assemblages of these ichnofacies are listed in

Table 1. Their distribution is not strictly controlled by bathymetry but by the zonation of oceanographic conditions such as currents, rates of sedimentation, and aeration (Osgood, 1970; Frey, 1971).

These six ichnofacies do not possess sharply delineated boundaries, and many trace fossils thought to be facies

TABLE 1.—*Bathymetric Zonation of Trace Fossil Assemblages (Modified from Seilacher, 1967; Frey, 1971).*

NONMARINE	
<i>Scoyenia</i> facies:	Contains <i>Isopodichnus</i> , certain ichnospecies of <i>Planolites</i> , and limulid trace fossils.
MARINE	
<i>Skolithos</i> facies:	Littoral. Rapid sedimentation and erosion, shifting substrates. Contains <i>Skolithos</i> , vertical protrusive and retrusive spreite structures.
<i>Glossifungites</i> facies:	Littoral. Omission surfaces, stable substrates. Contains <i>Glossifungites</i> , well-developed protrusive spreite resulting from growth of producer.
<i>Cruziana</i> facies:	Infralittoral to circalittoral. Well-sorted sediments. Contains <i>Cruziana</i> and similar repichnia plus inclined, protrusive U-shaped spreite such as <i>Rhizocorallium</i> .
<i>Zoophycos</i> facies:	Circalittoral to bathyal. Impure silts and sand, no turbidite deposition. Contains tabular <i>Zoophycos</i> plus simple and efficient grazing trails.
<i>Nereites</i> facies:	Bathyal to abyssal. Pelagic sedimentation. Trace fossils preserved mostly on bedding planes of turbidites. Contains <i>Nereites</i> and other efficient grazing trails.

specific are now found to be facies crossing. As an example, *Thalassinoides*, commonly used to distinguish ancient shorelines, has been described from deepwater Upper Cretaceous sediments in California, where *Thalassinoides* was found associated with *Nereites*, *Zoophycos*, *Chondrites*, and *Spirophycus* (Kern & Warme, 1974). In the Tecumseh Shale, *Nereites* is found in shallow water sediments in the same bed with *Diplocraterion* and *Arenicolites*. *Nereites* is the index fossil for Seilacher's deep water (abyssal) *Nereites* facies. The appearance of such facies crossing forms does not mean they are useless in paleoecologic investigations. Thus, the entire trace fossil assemblage must be taken into consideration and not just one member. This is especially true for shallow water sediments where many different types of local environments can exist next to each other along the same shoreline.

CYCLOTHEMS

Moore (1929, 1931, 1936, 1950, 1966) recognized the existence of cyclothems in Upper Pennsylvanian strata in Kansas. In 1936, he coined the term "megacyclothem" for a cycle of cyclothems that occur in repeated sequences. Megacyclothems are commonly described stratigraphically upward as follows: 1) clastic unit composed of a basal sandstone overlain by sandy shale and finally coal; coal is overlain by shale, which may or may not be fossiliferous; 2) relatively thick, fusulinid "lower" limestone; 3) shale; 4) thin, fusulinid "middle" limestone; 5) black fissile shale, overlain by a yellow or gray clayey shale; 6) thick, light gray, wavy-bedded, fusulinid "upper" limestone; 7) shale; 8) "super" limestone; and 9) shale. Particularly

impressive is the repetition of essentially different smaller, cyclic units four times within Missourian and Virgilian time. These four megacyclothems are shown in Figure 2.

Many of the constituent cyclothems of a megacyclothem are incomplete. That is, certain members may be missing, but a general pattern nevertheless is developed. The shale units are considered to be mainly nonmarine except for those areas where nearshore, marine invertebrates are found. Special emphasis is placed on the role of the shale unit at the base of each megacyclothem (Fig. 2). Each of these shales (Lawrence, Stull, and Tecumseh) is thought to represent a transgressive phase from nonmarine to marine. As stated above, continental conditions were represented by a basal sandstone, conglomeratic at the bottom, which was followed upward by a sandy shale with plant fragments. A coal overlies this shale and is in turn overlain by a shale, which may contain nearshore invertebrates. This sequence is interpreted to represent a transgression. Continental deposition gradually came to an end, marked by the inundation of a coal swamp with the beginning of marine conditions, and culminating with carbonate deposition at the fully marine phase.

The model is therefore straightforward. During shale deposition, the seas were withdrawn either completely or partially. Fully marine conditions returned with the next transgressive phase. The dividing line between continental and marine conditions within a shale unit can be drawn with accuracy only at the end of coal deposition.

The interpretation of shale units *within* megacyclothems is more difficult because certain constituent members are commonly absent. The Rock Lake Shale is such an example.

Ideally, a transgressive sequence indicating a transition from nonmarine to marine conditions should be recognized by a change from trace fossils of the nonmarine *Scoyenia* facies to those of the intertidal *Skolithos* or *Glossifungites* facies. Entirely marine transgressions should also be marked by a transition from the *Skolithos* or *Glossifungites* facies to the deeper water *Cruziana* facies (Table 1).

ABSENCE OF BODY FOSSILS

Trace fossils and body fossils are generally not preserved together. Soft-bodied trace-makers have a low potential for fossilization; their absence is easily explained. However, many trace fossils are produced by organisms known to possess potentially fossilizable skeletons. In the latter case, the absence of skeletal material is commonly explained by the action of destructive processes such as abrasion or diagenesis (Seilacher, 1970). In trace fossil-bearing sequences, it is therefore not necessary to assume that the absence of body fossils signifies an absence of faunal elements originally within the sediment.

Heckel (1972, p. 259) discussed the general absence and poor preservation of body fossils in several gray shale units in the Upper Pennsylvanian of Kansas. According to him, these forms are small and thin-shelled, and deteriorate rapidly in outcrop. He concluded that many of these faunas were reduced in number because of lowered salinities and turbidity caused by rapid sedimentation from streams or rivers.

Thirty different types of trace fossils are here described from the Rock Lake Shale. Many of them are thought to have been formed by bivalves, gastropods, arthropods, and other organisms with fossilizable calcareous skeletons. No shell material has been found in these trace fossil-bearing beds except for one shell of *Lingula* which is chitinophosphatic (Pl. 7, fig. 2). The Rock Lake Shale possessed a very diversified and abundant fauna and not one restricted by lower salinities and turbidity associated with the deposition of silt and fine-grained sand. It would seem reasonable to assume that many of the trace-making organisms existed throughout the deposition of the muds that occur above and below these thin lenses of siltstone and fine-grained sandstone, and that rapid deposition of these small lentils fortunately recorded the presence of organic activity.

Body fossils in the Stull and Tecumseh Shales are infrequently found in beds of siltstone containing trace fossils. Body fossils are commonly found in units of mudstone that display subconchoidal fracture. In fact, this fracture is so distinctive that it is possible to predict where body fossils will occur. These fossils dissolve rapidly when exposed to water.

The presence of shell material in these shale units would appear to be a function of preservation. Sediments, such as siltstone and sandstone, would have a relatively high permeability to ground water, which can rapidly dissolve constituent skeletal material. Dissolution would not occur as rapidly in the less permeable mudstone units. Stephan *et al.* (1973) described the diagenetic removal of shell material from Pleistocene barrier islands along the Carolina coast. Shells were completely leached by ground water with no disruption of primary bedding features, and therefore no evidence remained to suggest that shell material was once present.

DISTRIBUTION OF TRACE FOSSILS

The distribution of trace fossils, as studied during this investigation, is controlled by 1) depositional environment and, ultimately, 2) lithology. The controls imposed by environmental factors are discussed elsewhere in this paper.

Lithology plays an important role in determining the final distribution of trace fossils. Traces produced in dominantly mud environments have a very poor fossilization potential. The same is true for the traces of small

animals produced in coarse-grained clastic sediments. Commonly, trace fossils are found along bedding planes, and, therefore, surfaces with a high potential for fossilization of sedimentary structures will display both organic and inorganic structures well. A sediment able to display fine tool marks as shown in Plate 13, figure 6, can also display very small ichnofossils. Problems of trace fossil preservation have been discussed by Osgood (1970).

The trace fossils associated with each of the four units studied are listed in Tables 2, 3, 4, and 5. At first glance, it is obvious that geographic distribution of ichnofossils is not uniform within the same unit. At least one locality in each unit has no trace fossils at all. Differences in preservation, diagenesis, and original faunal content of the sediment can explain most of these omissions. In the case of the Stull and Tecumseh Shales, soft-sediment deformation has almost totally obliterated some of the original bedding features. This compounds the preservation problem.

The Rock Lake Shale contains the most abundant and diverse assemblage of trace fossils (Table 2), and most

TABLE 2.—*Distribution of Trace Fossils in the Rock Lake Shale Member.* (Designations of *a* and *b* indicate more than one trace fossil horizon per locality; *a* is stratigraphically above *b*. Refer to Figure 5 for columns.)

ICHNOGENUS	LOCALITY				
	1	2	3	4a	4b
<i>Asteriacites</i>			X		X
<i>Bergaueria</i>					X
<i>Chevronichnus</i>			X		X
<i>Chondrites</i>			X		X
<i>Cochlichnus</i>			X		X
<i>Conostichus</i>					X
<i>Curvolithus</i>		X	X		X
<i>Cruziana</i>			X		
<i>Didymaulichnus</i>		X	X		X
? <i>Gyrochorte</i>			X		
<i>Isopodichnus</i>		X	X		X
<i>Lingulichnus</i>		X	X		X
<i>Lockeia</i>	X	X	X		X
cf. <i>Lorenzina</i>			X		
<i>Microspherichnus</i>			X		X
<i>Planolites</i>	X		X		X
<i>Rusophycus</i>			X		
<i>Scalartituba</i>			X		
<i>Tigillites</i>					X
? <i>Taenidium</i>			X		X
<i>Tomaculum</i>	X		X		
? <i>Trichichnus</i>					X
Arthropod trail A			X		
Arthropod trail B		X	X		
Branched burrow		X	X		X
Loop burrow			X		
Mottled burrows				X	X
Plowing trails	X				
Resting impressions ..			X		X

TABLE 3.—Distribution of Trace Fossils in the South Bend Limestone Member. (Refer to Figure 5 for columns).

ICHOGENUS	LOCALITY				
	1	2	3	4	5
<i>Arenicolites</i>	X			X	
<i>Asterichnus</i>					X
<i>Asterophycus</i>					X
<i>Aulichnites</i>					X
<i>Chondrites</i>	X				X
<i>Crossopodia</i>					X
<i>Diplocraterion</i>	X			X	
<i>Gordia</i>					X
<i>Margaritichnus</i>				X	X
<i>Planolites</i>			X	X	X
<i>Rhizocorallium</i>				X	

of these ichnogenera are found at Localities 3 and 4. To the north, diversity decreases from Localities 2 to 1. It has been shown by the study of coprolite orientation that wave activity at Locality 1 was greater than at Locality 3 in the center of the study area (see discussion of *Tomaculum*). It is possible that many of these siltstone and fine-grained sandstone lenses were reworked by waves to the degree that many of the traces were destroyed. Another possibility may be that higher energy conditions to the north were less favorable than the calmer waters at Localities 3 and 4. Therefore, fewer animals lived in the north. No trace fossils have been found at Locality 5 because no siltstone or fine-grained sandstone was deposited or preserved at that locality.

The base of the South Bend Limestone is a medium-bedded, calcite cemented sandstone. At Locality 5, the base of the unit loses a considerable amount of this cement and is more a pure sandstone. Bandel (1967a) described from this locality a diverse ichnofauna that is unparalleled in any of the other four outcrops of South Bend Limestone. Of the ichnogenera described by Bandel (1967a), *Asterichnus*, *Asterophycus*, *Crossopodia*, and *Gordia* are confined to Locality 5. No new ichnotaxa have been discovered at that outcrop and the reader is referred to Bandel (1967a) for a detailed description of these four ichnogenera. It would appear that this increased abundance of trace fossils could be partially related to a decrease in calcite cement, which improved the preservational potential.

The distribution of trace fossils in the Stull Shale (Table 4) and the Tecumseh Shale (Table 5) shows no well-defined pattern other than that diversity and abundance are markedly pronounced at only a few localities. This distribution is primarily related to lateral lithologic

TABLE 4.—Distribution of Trace Fossils in the Stull Shale Member. (Designations of *a* and *b* indicate more than one trace fossil horizon per locality; *a* is stratigraphically above *b*. Refer to Figure 6 for columns.)

ICHOGENUS	LOCALITY							
	1	2a	2b	3	4	5	6	7
<i>Asteriacites</i>						X		X
<i>Aulichnites</i>								X
<i>Chondrites</i>	?					X		
<i>Didymaulichnus</i>	X				X			
<i>Lockeia</i>						X		
? <i>Nereites</i>						X		
<i>Planolites</i>	X	X	X		X	X		X
<i>Teichichnus</i>						?		X
Branched burrows						X		X
Meandering trail						X		X

TABLE 5.—Distribution of Trace Fossils in the Tecumseh Shale. (Designations of *a* and *b* indicate more than one trace fossil horizon per locality; *a* is stratigraphically above *b*. Refer to Figure 9 for columns.)

ICHOGENUS	LOCALITY							
	1	2	3	4a	4b	5	6	7a
<i>Arenicolites</i>				X				
<i>Aulichnites</i>						X	X	
<i>Chondrites</i>							?	
<i>Cochlichnus</i>			X					
<i>Didymaulichnus</i>				X				
<i>Diplocraterion</i>				X				
<i>Fucusopsis</i>				X				
<i>Lockeia</i>	?		X		X			
<i>Neonereites</i>				X				
<i>Nereites</i>	X		X	X				
<i>Planolites</i>	X		X	X	X	X	X	X
<i>Tigillites</i>				X				
? <i>Taenidium</i>							X	
Curved burrows				X				
Gastropod trail	X						X	
Mottled burrows				X				X

variations characterizing each unit (Fig. 6, 9). The lowest diversity of trace fossils is found in the Stull Shale, and lithologies within that unit vary sharply both within and between outcrops. The lithologies of the Tecumseh Shale are fairly constant within an outcrop but not between outcrops. It would appear that both the Stull and Tecumseh Shales were deposited in fluctuating or diverse environmental settings, which explains somewhat the distribution of trace fossils found.

INTERPRETATION

ROCK LAKE SHALE AND
SOUTH BEND LIMESTONE MEMBERS

The depositional environment of the Rock Lake Shale Member in northeastern Kansas is interpreted to be near-shore, marginal marine (?lagoonal) followed by a major transgression and the deposition of the South Bend Limestone.

Russell (1972) and Heckel (1975) interpreted the Rock Lake Shale in Nebraska and southeastern Kansas to represent a regressive sequence. According to them, this regression was followed by subaerial exposure and finally a transgressive phase, which was marked by deposition of the South Bend Limestone. There is no well-defined evidence for a regression during Rock Lake time within the study area. No evidence for subaerial exposure was recognized. A burrow-mottled zone directly beneath the base of the South Bend Limestone Member (Loc. 4) might represent a period of nondeposition and intense infaunal reworking of the sediment.

It is possible that water depths were greater in northeastern Kansas, and the regressive phase was simply not recorded or did not occur there because of the greater depth of the Forest City Basin. An alternate hypothesis could be that the regression was not eustatic in origin but was caused by local conditions of epeirogenesis or sedimentation. Lins (1950, fig. 1) traced the areal extent of the Tonganoxie River Valley (lower Virgilian, Fig. 1) in northeastern Kansas. The outcrops of Rock Lake Shale studied occur on the north and south banks of this valley (Loc. 1 and 5, respectively). Localities 2, 3, 4 are situated in the center of the valley and are erosional remnants of the river. Trace fossil diversity and abundance in the Rock Lake Shale increase from the north (Loc. 1) to the center of the outcrop belt (Loc. 2, 3, 4), and then decrease to the south (Loc. 5). Although preservation of the ichnofauna is dependent upon the presence of the siltstone lenses, the deposition of the siltstone unit may have been controlled by negative relief, which resulted in increased circulation and higher biotic diversity during Rock Lake time. This negative relief may have been fully exploited by the Tonganoxie River much later. The Tonganoxie River eroded down into the Stoner Limestone, directly beneath the Rock Lake Shale (Lins, 1950).

The sediments of the Rock Lake Shale Member, which commonly contain trace fossils, are thin-bedded lenses (commonly 5 to 10 mm thick) of siltstone or fine-grained sandstone. Only near the top of the Rock Lake Shale, at Locality 4, are burrows preserved in sediments with increased clay content. The siltstone or fine-grained sandstone is micaceous and commonly contains plant fragments (Pl. 13, fig. 3). Flaser bedding is common. Flaser

bedding is present in many different types of sedimentary environments and cannot be used as an independent environmental tool (Terwindt & Breusers, 1972). However, the fact that Rock Lake sediments have not been intensively reworked by physical processes supports the interpretation for a quiet water environment.

The regional setting for the deposition of the Rock Lake Shale Member strongly indicates that a shallow water, nearshore environment existed in northeast Kansas. The Rock Lake Shale was thought to be continental and regressive in Nebraska (Russell, 1972) and regressive in southeastern Kansas (Heckel, 1975). Peabody (1952) considered the Rock Lake Shale at Garnett in Anderson County, Kansas, to represent a lagoonal deposit. This locality contains the *Garnettius* assemblage which Moore (1966, fig. 7) considered typical of a "somewhat brackish-water lagoon." This body fossil fauna is not found in northeastern Kansas (Moore, 1966, fig. 7). A coal bed is present in the Rock Lake Shale in Franklin County (Ball *et al.*, 1963). Farther north in Johnson County, desiccation cracks have been found in the Rock Lake Shale (P. H. Heckel, pers. commun., 1971). Heckel & Baesemann (1975) studied conodont distributions in the Stanton Limestone in northeast Kansas and concluded that deposition in the upper part of the Rock Lake Shale was essentially nonmarine and at the base of the South Bend Limestone was transgressive marine.

Trace fossils present in the Rock Lake Shale support the assumption that deposition occurred in a "schizohaline" environment (see discussion of Salinity). One of the most common trace fossils is *Isopodichnus*, a form thought to be an indicator of freshwater environments (Seilacher, 1970). *Cochlichnus* is found in brackish water phases of the Upper Carboniferous cyclothems in Germany (Seilacher, 1963). Lingulid brachiopods, thought to have produced *Lingulichnus*, can tolerate brackish water conditions (Rudwick, 1970). *Chondrites* has been reported only in marine sediments (Simpson, 1957). *Scalartuba* is another marine indicator (Conkin & Conkin, 1968). The many actinian burrows, *Bergaueria* and *Conostichus*, represent marine conditions. It is possible that the streams that deposited the small lenses of siltstone also contributed to periodically reduced salinities. A similar situation is known to occur along the Texas coast where springtime runoff reduced salinities within the bays (Ladd, 1951). Therefore, *Isopodichnus*, *Cochlichnus*, and *Lingulichnus* would represent periodic declines in salinity.

A major environmental change occurred with the beginning of South Bend Limestone Member deposition. This change marks the start of a transgression which can be observed by a change in 1) lithology, 2) body fossils,

and 3) trace fossils. The base of the South Bend Limestone, a calcite-cemented sandstone, grades approximately halfway up the unit into a fossiliferous limestone (Ball *et al.*, 1963; Moore & Merriam, 1965). The base of the South Bend Limestone also marks the first appearance of well-preserved body fossils (*Aviculopecten* and *Orthomyalina*). Commonly these bivalves form plasters along bedding planes and are found in shallow to intertidal environments (Newell, 1937, 1942).

Well-developed, vertical U-tubes that occur at the base of the South Bend Limestone, are much larger than any trace fossils found in the underlying Rock Lake Shale. Two types of U-tubes exist. *Arenicolites* forms, without spreite and with packed burrow walls are common, as are spreite-bearing *Diplocraterion*. These types of burrows are indicative of the *Skolithos* facies (Seilacher, 1967). Associated with these U-tubes are large, well-developed *Chondrites* networks and ?anemone resting impressions, *Margaritichnus*. At the southernmost locality (Loc. 5), U-tubes are absent, and this locality has been interpreted to belong to the *Cruziana* facies (Bandel, 1967a). Stratigraphically higher in the South Bend Limestone, obliquely oriented forms of *Rhizocorallium* are found. Rhoads (1967) demonstrated that burrow orientations vary with respect to increasing depth in shallow water environments. Vertical burrows dominate in the intertidal zone. During periods of low tide, animals are able to retreat to the bottoms of their burrows to avoid desiccation. In subtidal areas, animals are not forced to construct vertical burrows because they are not greatly influenced by tidal fluctuations. Therefore, these burrows tend to be oblique or parallel to the surface of the sediment. Ager & Wallace (1970) have recognized similar relationships in uppermost Jurassic strata along the northern coast of France.

It would appear that deposition of the Rock Lake Shale Member occurred in a lagoonal environment that was separated from wave and current activity and normal marine conditions by an offshore barrier. This barrier consisted of the basal part of the South Bend Limestone which contains large, vertical burrows. Farther offshore, in deeper water, obliquely oriented forms of *Rhizocorallium* were produced. The base of the South Bend Limestone is a relatively clean sandstone. Even farther offshore, normal marine conditions and limestone deposition occurred as represented by the upper part of the South Bend Limestone, a wackestone.

STULL SHALE MEMBER

A transgressive phase can be recognized in the Stull Shale Member but not one as suggested by Moore (1936). The unit is interpreted to be regressive prior to coal deposition, with a transgression occurring after coal deposition. The depositional environment below the coal can be

characterized as nearshore, but not continental. The presence of many different trace fossils (*Asteriacites*, *Teichichnus*, *Planolites*, *Didymaulichnus*, *Aulichnites*, and *Chondrites*) suggests that a fairly varied infauna and epifauna existed prior to coal deposition. *Asteriacites* is generally thought to be of starfish or ophiuroid origin (Seilacher, 1953b). Recent representatives of these organisms are known to tolerate reduced salinities, but not fresh water (Ladd, 1951; Segerstråle, 1955). In addition, typically retrusive forms of the wall-like spreite *Teichichnus*, one of which is several tens of centimeters high, suggest rapid rates of sedimentation. *Teichichnus* is thought to have been produced by a wormlike organism moving its dominantly horizontal, tubular burrow vertically through the sediment. This type of behavior has been observed with *Nereis diversicolor* on the North Sea tidal flats (Seilacher, 1957). Burrow migrations can be the result of sedimentation (upward movement) and erosion or active burrowing (downward movement). Similar interpretations have been proposed for the development of another spreite structure, *Diplocraterion*, by Goldring (1962). *Didymaulichnus* suggests the occurrence of molluscs with ditactal musculature, most likely gastropods (Young, 1972; Schäfer, 1972). *Aulichnites* also argues for the existence of gastropods (Fenton & Fenton, 1937). *Chondrites* is typically a marine trace fossil (Simpson, 1957).

Since Pennsylvanian coal-producing vegetation is not thought to have tolerated prolonged exposure to salt water, abundant plant debris in low gradient basins is also indicative of shallow water, nearshore conditions (Wanless *et al.*, 1969, p. 112). Many of these plant fragments are structurally well-preserved and do not suggest extensive transportation prior to deposition.

Sedimentologically, the Stull Shale is composed of alternating beds of sandstone and clays. The clays are typically structureless, rarely bedded, and have not been observed to contain root structures, although plant debris may be common. The sandstone units are typically thin-bedded, one to several tens of millimeters thick, and are commonly flaser bedded (Reineck & Wunderlich, 1968). These thin, alternating beds of sand and clay are known from subtidal, intertidal, lagoonal, fluvatile, and deltaic environments (Terwindt & Breuser, 1972, and references therein) and are not indicative of one particular depositional setting. Wavy and lenticular bedding is also common.

Wanless *et al.* (1970) envisaged Pennsylvanian deltaic systems depositing sediments from the north into the Forest City Basin. Such deltas possessed gradients of less than half a degree. Channel-filling sandstone lenses are known near the top of the Stull Shale (Fig. 8) (Moore *et al.*, 1951). These sandstone lenses contain carbonized logs and other plant debris. Many of the thick-bedded

sandstone layers have been destroyed by soft-sediment deformation (Fig. 7).

It would therefore seem reasonable to suggest that during Stull time, a delta or delta-like system extended southward through what is now Jefferson and Douglas Counties, Kansas. South of this area, coarse-grained clastics commonly disappear (Ball *et al.*, 1963). In the north, low-gradient clastic lobes built up to sea level and were colonized by plants that now form the coal bed near the top of the unit (Wanless *et al.*, 1970). Subaerial exposure of the delta platform caused a shift in stream deposition and the development of other clastic lenses, which explains why few beds are continuous between and even within outcrops (Fig. 6). The subsequent compression of sediments of the exposed delta platform inundated the coal swamp with normal marine to brackish water. A similar model has been proposed for coal deposition in the Appalachian coal basins (Ferm, 1970). A sparse fauna consisting of *Chonetes*, *Juresania*, *Derbyia*, *Myalina*, *Aviculopecten*, and *Wilkingia* is found beneath the overlying Spring Branch Limestone (O'Connor, 1960; Ball *et al.*, 1963; Moore & Merriam, 1965). Above the coal, no trace fossils have been found. A major transgressive phase was initiated with the deposition of the Spring Branch Limestone.

It is difficult to place the trace fossil-bearing units of the Stull Shale Member in Seilacher's (1967) bathymetric ichnofacies scheme (Table 1). The unit is characterized by 20 percent cubichnia, 20 percent repichnia, 60 percent fodinichnia, and 10 percent pascichnia. The Stull lacks characteristic forms of the *Scoyenia* facies and does not have the predominance of vertical dwelling burrows of either the *Skolithos* or *Glossifungites* facies. The absence of well-sorted sands and distinctive repichnia and oblique spreite burrows also excludes the *Cruziana* facies.

TECUMSEH SHALE

By the study of trace fossils, a transgression can be recognized locally in the Tecumseh Shale. The lower part of the unit studied in this investigation consists of thin- to medium-bedded sandstone (Loc. 2 and 7). At Locality 2, the thicker-bedded sandstone beds are severely altered by soft-sediment deformation. Almost all of the sandstone beds within the unit contain plant fragments. Those that do not have been physically reworked by wave action. A coal unit was not found within the area studied, although one is supposed to exist in the shale (Moore, 1950).

Trace fossils collected from the lower part of the Tecumseh Shale do not reflect any particular orientation due to currents, sedimentation, or erosion. Most of the ichnofauna is preserved in thin beds (a few centimeters thick), of occasionally cross-bedded sandstone. The ichnofauna is comprised of *Planolites*, *Aulichnites*, and gastropod trails, which are all preserved on bedding planes.

Plant fragments are common. These sandstone beds appear to represent a shallow water area, relatively free of continuous wave action. This is reflected in the absence of physical reworking of the thin-bedded sediments and the absence of vertical burrows. Because plant fragments are common and abundant throughout the Tecumseh Shale, it is probable that deposition was probably close to a positive area (i.e., the shoreline).

At Localities 3 and 4, a different suite of trace fossils is locally introduced near the top of the unit. This ichnofauna consists of the vertical U-tubes *Arenicolites* and *Diplocraterion*. Such U-tubes are typically thought to represent Seilacher's (1967) *Skolithos* facies (Table 1). The *Skolithos* facies is thought to represent near strand line conditions with wave agitation sufficient to provide suspended nutrients in the water body, which would enable a community of suspension-feeding organisms to become established. Such environmental conditions would differ from those in the lower part of the unit where burrows of filter-feeding organisms have not been found. None of the traces in the upper part of the unit reflect development by growth of the producer as is common in areas of nondeposition (*Glossifungites* facies). *Diplocraterion* is preserved in a thin-bedded, ripple-marked sandstone containing occasional pyrite nodules. This sandstone is only a few centimeters thick and only the vertical limbs of *Diplocraterion* and spreite are visible (Pl. 5, fig. 3b). The vertical burrow *Tigillites* is also found at this horizon.

Nereites and *Neonereites biserialis* are associated with *Arenicolites*, *Diplocraterion*, and *Tigillites*. Commonly *Nereites* and *N. biserialis* are found on the same rock slab. Seilacher & Meischner (1965) and Chamberlain (1971a) considered that the hypichnial expressions of *N. biserialis* were produced by the same process that produced the lateral lobes of *Nereites*. Transverse cross sections through *N. biserialis* do not show a *Nereites* structure above the hypichnial lobes (Pl. 9, fig. 1b). Although the absence of a *Nereites* structure does not prove a link between *N. biserialis* and *Nereites* in the Tecumseh Shale, it does demonstrate that *N. biserialis* was produced while the sediments were still being reworked by wave action and therefore close to the sediment-water interface. The presence of *N. biserialis* can be interpreted to represent increased water agitation and probably transgressive conditions.

In Shawnee County, Johnson & Adkison (1967) interpreted the Tecumseh Shale to have been deposited in essentially continental conditions before a transgression occurred prior to deposition of the overlying Ozawkie Limestone Member of the Deer Creek Limestone (Fig. 1). It would seem that the beginnings of the transgression that deposited the Deer Creek Limestone can be observed near the top of the Tecumseh Shale, at Localities 3 and 4, by the study of trace fossils. At Localities 2 and

6, nuculinid bivalves have been found. At Locality 6, bellerophonacean gastropods have been discovered in the same horizon as the bivalves. *Bellerophon* is also found in the base of the overlying Ozawkie Limestone (Moore & Merriam, 1965). These body fossils also reflect the beginning of marine conditions.

Fagerstrom & Burchett (1972) studied the depositional environment of the upper part of the Tecumseh Shale in southeast Nebraska. In Nebraska, the Tecumseh Shale is formally divided into three members. The basal member is the Kenosha Shale. This is overlain by the Ost Limestone, which is not found in Kansas. Above the Ost Limestone is the Rakes Creek Shale. According to

Fagerstrom & Burchett (1972), at the end of Ost time a major eastward regression of the shoreline occurred after which much of the Rakes Creek Shale accumulated in a subaerially exposed delta. Near the end of Rakes Creek time, a transgressive sequence was initiated prior to deposition of the Ozawkie Limestone. This interpretation fits very well with the relationships seen in the Tecumseh Shale within the area studied. The regressive phase is reflected by burrows not oriented by currents or produced by suspension feeders in the lower part of the outcrops, and the transgression by the development of burrows of suspension feeders (U-tubes and vertical single tubes) higher up in the unit.

CONCLUSIONS

The following conclusions can be drawn:

1) Trace fossils in the Rock Lake Shale Member are typical of freshwater, brackish, and marine conditions, indicating deposition in a low wave-energy, euryhaline environment.

2) The contact between the Rock Lake Shale Member and the lower part of the South Bend Limestone Member (a calcite-cemented sandstone) marks the beginning of a transgressive marine phase prior to limestone deposition in the upper part of the South Bend. This transgression is reflected by the ichnofauna found there.

3) Sedimentation in the Stull Shale Member, below the coal bed(s), is not predominantly continental as previously thought. Deposition appears to have occurred under shallow water marine conditions and is not indicative of a transgressive phase throughout the unit as previously considered.

4) A well-defined, but local, transgressive, marine phase can be observed within the Tecumseh Shale. The lower part of the unit is interpreted not to be entirely continental as previously thought.

5) The depositional environments of the Stull Shale Member and Tecumseh Shale at the base of two different megacyclothems reflect shallow water deposition but are not analogous either lithologically or ichnologically.

6) Lateral variation within the clastic units is much greater than in carbonate units studied by others (Toomey, 1969a; Troell, 1969).

7) Nonmarine, marine, and intermediate marine environments are recorded in the shale units. The study and interpretation of them provides a better understanding of the environmental changes within cyclothems than do many of the fossiliferous limestone units deposited during marine invasions.

PALEONTOLOGIC DESCRIPTIONS

NOMENCLATURE

The *International Code of Zoological Nomenclature* recognizes the availability of only pre-1930 names for ichnotaxa (Osgood, 1970; Häntzschel & Kraus, 1972; Häntzschel, 1975, p. W24-27). In order to correct this, a proposal was submitted to the Commission, but so far no action has been taken on it (Häntzschel & Kraus, 1972). Therefore, following the convention recommended by Häntzschel (1975) in the *Treatise on Invertebrate Paleontology*, all names for trace fossils cited herein are treated as available and subject to the Law of Priority under the rules of the I. C. Z. N.

TERMINOLOGY

Seilacher's (1953a; 1964a,b) descriptive terminology for ichnotaxa is primarily used here in addition to that of Martinsson's (1965, 1970), which allows for descriptive terms to be used as nouns.

CLASSIFICATION

Trace fossils described are interpreted to belong to one of the five ethologic groups proposed by Seilacher (1953a, p. 432-434).

DESCRIPTION OF TRACE FOSSILS

Although pre-1931 names for trace fossils can be treated as genera and species, all names used herein are classified as ichnogenera and ichnospecies. This procedure maintains uniformity and clearly designates the taxa as trace fossils (Häntzschel, 1975).

Descriptions of ichnotaxa here are in a format similar to that used by Häntzschel (1975). First, the morphologic "description" of a trace fossil is given with respect to size and relation to bedding. Under "discussion," the ethologic interpretation is stated which is followed by an interpretation of possible producers (where possible) and a discussion of facies relationships of the ichnotaxon.

The trace fossils are grouped below only in alphabetical order as in Häntzschel (1962, 1975). Some authors have listed the ichnofauna they studied under one of Seilacher's (1953a) five ethologic groups (Pfeiffer, 1968; Osgood, 1970; Chamberlain, 1971a). This procedure is not followed here. Simple alphabetical listing was adopted for ease in referring back to a particular ichnogenus, especially when many trace fossils are described. Informally named trace fossils are listed separately in alphabetical order after the formally named ichnogenera.

All specimens described and illustrated in this paper are housed in the Kansas University Museum of Invertebrate Paleontology (KUMIP).

Ichnogenus *ARENICOLITES* Salter, 1857

Plate 1, figures 2a-d

Type species.—*Arenicola carbonaria* Binney (1852, p. 192), subsequent designation by Richter (1924, p. 137).

Description.—U-shaped burrow, lacking spreite, oriented perpendicular to bedding plane. Diameter of burrows commonly 0.8 to 1.8 mm. Distance between arms of U-tubes, up to 70 mm. A zone about 3 to 5 mm wide is present around many of the U-tubes.

Discussion.—Domichnia of worms.

Arenicolites is associated in the same bed with *Diplocraterion*, containing well-developed, protrusive spreiten in the South Bend Limestone. However, most specimens found with *Diplocraterion* have circular "halo" structures around the limbs of their U-tubes, indicating spreite development had not occurred (Pl. 1, fig. 2d).

Arenicolites is not as well preserved in the Tecumseh Shale as in the South Bend Limestone. The base of the U-tube is never seen to protrude in hyporelief, and only paired, vertical burrows in epirelief give any indication of the burrows' presence. Plate 1, figure 2b shows the tops of vertical tubes along an upper bedding plane. In cross section, it is possible to detect the U-tube (Pl. 1, fig. 2c).

Arenicolites is commonly thought to represent the shallow water, intertidal environment of the *Skolithos* facies and the slightly deeper water *Cruziana* facies. In

these environments, sufficient organic material and water turbulence are available to enable filter-feeding organisms to survive (Seilacher, 1964, 1967; Farrow, 1967, p. 103). Recently, Jansa (1974, p. 241) questioned the shallow water environmental restrictions usually associated with *Arenicolites*. He quoted several recent examples in the literature of U-shaped burrows from depths up to 930 meters and felt that *Arenicolites*, in the Cambro-Ordovician Cow Head Group of Newfoundland, may have been constructed in water depths greater than 200 meters. *Arenicolites* has also been described in Ordovician turbidites from North Spain (Crimes *et al.*, 1974).

Occurrence.—South Bend Limestone Member (Loc. 1, 4) and Tecumseh Shale (Loc. 4a).

Ichnogenus *ASTERIACITES* von Schlotheim, 1820

Plate 1, figures 1a-c

Type species.—*A. lumbricalis* von Schlotheim, subsequent designation by Seilacher (1953b, p. 93).

Descriptions.—Small, starfish-shaped objects, preserved in convex hyporelief, rarely in concave epirelief. Commonly with five to six rodlike "arms" (5 to 6 mm long) projecting from a central knob or subcircular area (approximately 5 mm in diameter). Occasionally, arms display faint annulations.

Discussion.—Cubichnia of asteroids, or more probably ophiuroids.

The nomenclature and ethologic history of *Asteriacites* has been reviewed by Seilacher (1953b) and Häntzschel (1975). The presence of a central knob or disk strongly suggests that the producer was an ophiuroid.

Ophiuroids commonly bury themselves in the sediment with their central disk at the bottom of the burrow, their arm tips extending into the overlying water. Analogous behavior can be seen in modern *Amphiura* communities (Thorson, 1957, fig. 14). Starfish accommodate sudden influxes of sediment by moving upward within the substrate. The vertical repetition of *Asteriacites* traces has been discussed by Seilacher (1953b, fig. 3) from Lower Triassic sediments in Germany. The appearance of *Asteriacites* in the Rock Lake Shale also suggests that the trace fossil was produced by upward movement of the animal in the sediment. Plate 2, figure 1c shows a form of *Asteriacites* preserved in concave epirelief. The depression made by the starfish has been partially filled as sediment flowed together after the animal left its resting place. Whether this upward movement was in response to sedimentation or a normal process of burrow evacuation in search of a new resting place is problematical. No vertical repetitions of traces were found, but this could be a function of preservation and bedding.

Recent starfish and brittle stars have been recognized from shallow water to abyssal depths (Thorson, 1957; Hersey, 1967; Heezen & Hollister, 1971; Pequegnat *et al.*, 1972). Their traces are, however, only common in sedi-

ment interpreted to be shallow water deposits and are almost unknown from deep water, flysch deposits (Seilacher, 1953b, 1955, 1958, 1964; Książkiewicz, 1970). The presence of an abundant *Asteriacites* ichnofauna can therefore be considered a good criterion for shallow water deposition.

Although starfish impressions may indicate shallow water deposition, an analysis of recent starfish distributions clearly shows that *Asteriacites* may not necessarily be indicative of totally marine conditions. Many starfish are known to tolerate brackish conditions. Segerstråle (1957, p. 777) discussed the distribution of *Asterias rubens* and *Ophiura albida* from brackish areas of the Baltic Sea. These forms were sexually immature and displayed marked size reduction. Most of the starfish impressions from the Rock Lake Shale are about 15 mm in diameter. Apparently, some ophiuroids tolerate reduced salinities in the polyhaline bays along the Texas coast (Ladd, 1951, p. 137). If similar tolerances for reduced salinities existed for some starfish in the fossil record, the presence of *Asteriacites*, especially small specimens, should be used with care in the interpretation of normal marine environments.

Occurrence.—Rock Lake Shale Member (Loc. 3, 4b) and Stull Shale Member (Loc. 5, 8).

Ichnogenus AULICHNITES Fenton & Fenton, 1937

Plate 2, figure 3

Type species.—*A. parkerensis*, by original designation.

Description.—Bilobed sinuous structure up to 18 mm wide with a central furrow, preserved in convex epirelief. Lobes have smooth to undulating surface.

Discussion.—Pascichnia of a gastropod (Fenton & Fenton, 1937).

By original definition, the surface of *Aulichnites* displays "oval layers which are concave anteriorly" (Fenton & Fenton, 1937, p. 1079). These structures are absent from the material described here, and the medial furrow is not as deep as that figured by the Fentons. The material has been included in *Aulichnites* primarily because it is bilobed and is preserved in convex epirelief.

Occurrence.—Stull Shale Member (Loc. 8) and Tecumseh Shale (Loc. 5, 6).

Ichnogenus BERGAUERIA Prantl, 1946

Plate 2, figures 1a-d

Type species.—*B. perata*, by original designation.

Description.—Small, subhemispherical structures, about 13 mm in diameter, and 5 mm high. Small depression common on bottom.

Discussion.—Cubichnia of actinian or actinian-like animal.

Small hemispherical structures such as these have been described from many geographic areas, and most are from

lower Paleozoic (Cambrian and Ordovician) strata, by Prantl (1944, 1946), Lessertisseur (1955), Häntzschel (1958), Radwański & Roniewicz (1963, p. 9), and Arai & McGugan (1968, 1969). *Bergaueria* is also known in Upper Jurassic rocks in France and England (Fürsich, 1974c). The nomenclatural history and synonymy of these structures were reviewed by Alpert (1973) who believed that *Bergaueria* was produced by an actinian sea anemone. The hemispherical shape is the result of the anemone settling into the uppermost layers of the sediment surface. The specimens of *Bergaueria* from the Rock Lake Shale are interpreted to have been made in a similar manner.

In cross section (Pl. 2, fig. 1c), it is possible to observe that *Bergaueria* protrudes into the surrounding sediment and that layers of sediment surrounding the trace fossil are pinched out by it. An investigation of a bedding plane, from which the trace fossil had been removed (Pl. 2, fig. 1b), shows a well-developed, cuplike depression undoubtedly made by the producer as it settled into a lens of silt.

Alpert (1973, p. 921) compared the behavioral pattern responsible for *Bergaueria* with that thought to produce *Conostichus*. Chamberlain (1971a) demonstrated that some forms of *Conostichus* may have been produced by sea anemones migrating upward in the sediment in response to detrital influx. Alpert argued that, since *Bergaueria* does not reflect similar upward migration, the ability of sea anemones to move upward in the sediment as a response to sedimentation may have evolved sometime between the Ordovician and Pennsylvanian, when *Conostichus* was most commonly produced (Häntzschel, 1975). After studying *Bergaueria* from the Rock Lake Shale, it is apparent that at least a few actinians had not mastered this skill by the Late Pennsylvanian, and they had not done so even by the Late Jurassic (Fürsich, 1974c).

Two species of *Bergaueria* are known. Alpert (1973, p. 921-922) introduced *B. radiata* for small structures with "distinct wide to prominent radial ridges" around "a central depression." These ridges are not present in the material described here. The type species *B. perata* is most similar to the Rock Lake specimens in that both have a small, basal, centrally located depression and a reasonably smooth surface. Rock Lake Shale specimens are much shallower than *B. perata* and are more similar to *B. radiata* in that respect (Alpert, 1973, p. 1, fig. 9). Therefore, the Rock Lake Shale material has features common with both species and because only a few specimens were found in the Rock Lake Shale, no new species have been designated. They are referred to *Bergaueria perata*, the type species.

Seilacher (1964a) considered *Bergaueria* to be an indicator of shallow water deposition.

Occurrence.—Rock Lake Shale Member (Loc. 4b).

Ichnogenus CHEVRONICHNUS Hakes, ichnogen. nov.

Type species.—*C. imbricatus* Hakes, *ichnosp. nov.*

Holotype.—KUMIP 107,822.

Diagnosis.—Troughs in sediment. Sides of troughs composed of imbricated sheets of sediment meeting at center of trough to form a "V."

CHEVRONICHNUS IMBRICATUS Hakes, ichnosp. nov.

Plate 3, figures 1a,b; Plate 4, figures 1a,b

Description.—Slightly sinuous to curved grooves preserved in concave epirelief. Structures are commonly 6 to 7 mm wide, up to 0.2 m long, and about 1 mm deep. Sides of each groove are composed of small, imbricated, overlapping sheets of sediment which connect in the apex of the groove to form a broad "V." Small almond-shaped depressions can occasionally be found at the ends of the grooves, in which case the V's may point either toward or away from the depression. Grooves are deepest where the traces intersect crests of ripples or local thickenings of lenses.

Discussion.—Repichnia of bivalves.

Several animals are known to produce ribbonlike traces with V-shaped markings in the recent environment. The gastropod *Polynices duplicatus* can produce a V-shaped furrow as it moves through the top few millimeters of sediment (Howard & Dörjes, 1972, fig. 3d), as can *Hydrobia ulvae* (Baldwin, 1974, fig. 2b). Some bivalves are also known to make similar structures (Abel, 1935, fig. 217).

The markings from the Rock Lake Shale are grooves, and some show development of a chevronlike pattern within the groove. The Rock Lake specimens are seldom linear but are most commonly curved (Pl. 3, fig. 1a) or even circular (Pl. 3, fig. 1b), and commonly intersect. They have not been observed to be parallel, as if oriented by currents. The sediment forming the sides of the groove is strongly imbricated in well-developed layers. Many of the grooves have almond-shaped depressions at one end (Pl. 3, fig. 1a; Pl. 4, fig. 1a). On the underside of the bed, directly beneath these almond-shaped impressions, the bivalve resting impression, *Lockeia*, has been found. It is obvious that these epichnia are the expression of *Lockeia*, which is most commonly preserved in convex hyporelief. Similar depressions have been figured by Seilacher (1953b, pl. 12, fig. 1b) and Eagar (1974, fig. 8) and attributed by them to *Lockeia* (= *Pelecypodichnus* Seilacher).

The presence of *Lockeia* at one end of the chevron trail provides an explanation for the origin of many of these trace fossils. Abel (1935, fig. 217) showed *Cardium edule* plowing through the sediment in very shallow water (Pl. 4, fig. 1b). The trail left by the animal was a well-developed V-shaped groove. Imbrication was missing. It is reasonable to assume that eventually the animal

would produce a resting impression at the end of its trail which, given proper conditions for fossilization, could be preserved as *Lockeia*.

A bivalve fauna existed during the deposition of the Rock Lake Shale; *Lockeia* is a very abundant trace fossil. Many of the bivalves, during their foraging of the sediment, cut into the tops of thin lenses of silt and clay. The edge of their shell margins would then serve as an efficient plow, creating small groove-shaped trails in the sediment. Given a plastic medium, small flows of sediment would be pushed out to the side similar to the manner in which a snow plow folds successive layers of snow back along the side of a road. The V's produced would then point in the direction of motion. Plate 4, figure 1a shows the chevron trails of a bivalve as it was apparently decelerating and coming to a stop. There is an almond-shaped depression at the end of the trails which roughly conforms to the two fold symmetry of a bivalve. More importantly, the sediment to the left of the depression has been pushed and divided by the bivalve as it came to rest.

It is not possible to conclude that all such trails have been made by bivalves. However, the trails, with epichnia expressions of *Lockeia* at one end, argue for a bivalve origin for some of them.

Lockeia and *Chevronichnus* are transitional or can grade into each other, and it might be logical to consider the chevron trails ichnospecies of *Lockeia*. A similar example is the locomotion trail, *Cruziana*, which has been considered to include the resting impression, *Rusophycus*, because they, too, are transitional (Seilacher, 1970). This, however, has been widely contested (Osgood, 1970; Orłowski *et al.*, 1971; Birkenmajer & Bruton, 1971; Radwański, & Roniewicz, 1972; Crimes, 1975; Häntzschel, 1975). As another example, Fürsich (1973) grouped *Ophiomorpha*, *Thalassinoides*, and *Spongiomorpha* together under *Spongiomorpha*. This has come under attack by Bromley & Frey (1974), who separated the three ichnogenera and suggested that the name *Spongiomorpha* be rejected. Bromley & Frey (1974) also listed cases in which many different types of burrows grade into one another and are still maintained as separated ichnogenera. Although there is precedence to lump the chevron trails described here under *Lockeia*, there is similar precedence not to do so. *Chevronichnus* and *Lockeia* are maintained as separate ichnogenera because they are morphologically distinct from each other and because they do not *always* occur connected. It is important to realize, though, that the two forms are transitional.

Occurrence.—Rock Lake Shale Member (Loc. 3, 4b).

Ichnogenus CHONDRITES von Sternberg, 1833

Plate 4, figures 2a-c

Type species.—*Fucoides lycopodiodes* Brongniart (1828, p. 72), subsequent designation by Andrews (1955, p. 127).

Description.—Small, branching structures, up to several millimeters in diameter, preserved in convex hyporelief and convex epirelief. Branches commonly straight to slightly curved, may cross each other but never intersect.

Discussion.—Fodinichnia of small, wormlike animal (Simpson, 1957).

The morphology of *Chondrites* is diverse, and many ichnospecies can be found in the literature (Osgood, 1970, p. 328; Chamberlain, 1971a, p. 234). Many of these were proposed because of variations in size, preservation, and angle of branching as a consequence of the fucoid concept.

The specimens of *Chondrites* described here are not preserved well enough for a detailed systematic investigation. Preservation is poor because most sediments are thin-bedded and few of the burrow systems are confined exclusively to a single bedding plane. This is especially true in the Rock Lake Shale (Pl. 4, fig. 2b), but to a lesser extent in the Tecumseh and Stull Shales. Specimens of *Chondrites* collected from the South Bend Limestone are better preserved and developed because of a relative increase in bed thickness. In all cases, the burrows are considered to have been produced endogenically as they always are preserved in convex relief. In the South Bend Limestone well-developed burrow systems stand in convex epirelief on ripple-marked bedding planes. Some of the burrows can be observed to curve upward, indicating that the producer was situated in a layer of sediment above the one in which the burrow system was preserved (Pl. 4, fig. 2c). Simpson (1957, fig. 2) and Osgood (1970, fig. 10, 12) figured burrow reconstructions demonstrating that some *Chondrites* systems originated at a point in the sediment above which the distal ends of the burrow system are found. Richter (1927, p. 218; 1928, p. 226) discussed the role of phobotaxis in the construction of the *Chondrites* burrow. In the South Bend Limestone, where the branching networks are closely packed, the burrows never intersect, but do cross one another (Pl. 4, fig. 2c).

To some extent, *Chondrites* is known to be a facies-crossing trace fossil. Seilacher (1955, fig. 5) documented *Chondrites* from Ordovician and Devonian flysch of Portugal, Cretaceous to Tertiary Alpine flysch in Europe, and the shallow water, Liassic and Dogger sandstones of Württemberg. Similar facies relationships have also been discussed by Simpson (1957, p. 489) and Seilacher & Meischner (1964, fig. 4). Crimes (1973, fig. 11) described the lack of facies control of *Chondrites* in the Paleocene and Eocene flysch in northern Spain. On the other hand, Chamberlain (1971b, fig. 6) has proposed a *Chondrites* facies for the Ouachita Geosyncline in Oklahoma. The *Chondrites* facies was intermediate between the *Zoophycos* facies and the much deeper-water *Nereites* facies. This relationship may be entirely valid for the Pennsylvanian of the Ouachita System, but quite obvi-

ously, *Chondrites* cannot be considered to be an *a priori* facies indicator in other geographic areas. Frey & Chowns (1972, p. 39) already questioned Chamberlain's proposed ichnofacies for similar reasons.

Although the distribution of *Chondrites* does not display bathymetric control, the ichnogenus can probably be considered a facies indicator for the marine environment (Simpson, 1957, p. 493). *Chondrites* is not yet known to occur in nonmarine environments (Seilacher, 1955, 1963, 1967; Toots, 1967; Daley, 1968; Smith & Hein, 1971; Bromley & Asgaard, 1972; Stanley & Fagerstrom, 1974; Gibbard & Stuart, 1974).

Occurrence.—Rock Lake Shale Member (Loc. 3, 4), South Bend Limestone Member (Loc. 1, 5), Stull Shale Member (Loc. 1, 5), and Tecumseh Shale (Loc. 4a, 6).

Ichnogenus COCHLICHNUS Hitchcock, 1858

Plate 5, figure 5

Type species.—*C. anguineus* Hitchcock, by monotypy.

Description.—Small, sinusoidal burrows in convex epirelief, rarely concave epirelief. Width of trace less than 1 mm and may be up to 40 mm long. Structures commonly follow bedding planes.

Discussion.—Repichnia and probably fodinichnia of a small, wormlike animal.

The synonymies and nomenclatural history of *Cochlichnus* were discussed by Michelau (1955), Böger (1964), Nowak (1970), and Häntzschel (1975). This trace fossil has been referred to as *Sinusites* by Seilacher (1963), Crimes (1970), and Nowak (1970), and incorrectly as *Belorhaphé* Ludwig, 1869, by Michelau (1955), and Böger (1964). *Belorhaphé* is characterized by angular bends rather than the smooth sinusoidal curves of *Cochlichnus*. Häntzschel (1975, p. W52) considered sinusoidal forms to be *Cochlichnus* and maintained *Belorhaphé* as a separate ichnogenus.

Cochlichnus has been described from many different geographic areas and from a wide range of paleoenvironments (Jessen, 1955; Seilacher, 1963; Häntzschel, 1975). Crimes (1970, p. 106) found *Cochlichnus* (= *Sinusites*) in the *Skolithos*, *Cruziana*, and *Nereites* facies of the lower Paleozoic of Great Britain, and considered it to be "facies independent." *Cochlichnus* is also known from flysch facies in Poland (Nowak, 1970, p. 163). Seilacher (1963, p. 82) discussed the facies-crossing relationships of *Cochlichnus*. *Cochlichnus* has been described from Precambrian strata in Australia, thought to have been produced in "moderately shallow, relatively quiet, offshore conditions" (Webby, 1970, p. 105).

On the other hand, *Cochlichnus* is a facies indicator in the Upper Carboniferous cyclothems of West Germany and is therefore of special interest. Michelau (1955) figured many specimens and considered the ichnogenus to represent an environment between the brackish *Plano-*

lites ophthalmoides facies and the nonmarine pelecypod facies for these cyclothems. Seilacher (1963, fig. 1; 1964) placed *Cochlichnus* near the beginning of a transgressive phase. Böger (1964) placed *Cochlichnus* near the end of a regressive phase but still assigned it to an intermediate environment in agreement with Seilacher's interpretation. Regardless of the exact stratigraphic position of *Cochlichnus* within the development of a cyclothem, there is general agreement that *Cochlichnus* represents an intermediate environment between fresh water and well-developed brackish conditions.

As suggested by Michelau (1955, p. 307), specimens of *Cochlichnus* were most probably produced by small worms lacking well-developed parapodia. Seilacher (1963, p. 82) thought that nematodes or annelids could be probable producers. Moussa (1968, 1970) compared sinusoidal trails from the Green River Formation (Eocene) of Utah and recent nematode trails from Puerto Rico and considered them to be morphologically similar. Michaelis (1972, fig. 2) described small sinusoidal trails produced by recent fly larvae in dune sands. The trails figured by Moussa and Michaelis were produced in concave epirelief which are only similar in preservation to *Cochlichnus* from the Tecumseh Shale. However, specimens of *Cochlichnus* from the Rock Lake Shale are typically preserved in convex epirelief. Additionally, none of the specimens of *Cochlichnus* are as long as the sinusoidal trails described by either Moussa or Michaelis. Such differences might possibly be explained by pinching and swelling of the siltstone lenses.

Occurrence.—Rock Lake Shale Member (Loc. 3, 4b) and Tecumseh Shale (Loc. 3).

Ichnogenus CONOSTICHUS Lesquereux, 1876

Plate 5, figures 2a,b; Plate 6, figures 1a-c

Type species.—*C. ornatus*, by monotypy.

Description.—Small, conical to subconical structures (approximately 20 to 40 mm in diameter and up to 20 mm long), preserved in full relief. External surface of structures uneven. May have crude longitudinal ribs, originating from apical end or may have series of wrinkles running around structure.

Discussion.—Domichnia of actinian-like organism, produced as the animal migrated upward in the sediment (Chamberlain, 1971a, p. 220).

The origin of *Conostichus* has received much discussion in the literature. Lesquereux (1876) originally considered it a plant fossil. Later, Fuchs (1895, p. 411) considered it a medusa. Branson (1961, 1962b) compared *Conostichus* to the strobilization stage of a scyphomedusan. Chamberlain (1971a, p. 220) summarized previous interpretations of *Conostichus* and strongly suggested that the structure was produced by the migration of an actinian-like organism upward through the substrate.

Chamberlain (1971b, p. 221) listed *Conostichus* as a "dwelling burrow." Häntzschel (1975, p. W146) placed *Conostichus* in his chapter on trace fossils or medusae *incertae sedis*.

Other interpretations have been advanced for *Conostichus*. It has also been interpreted as the conical burrow of a filter-feeding animal (Pfefferkorn, 1971, but only for *C. broadheadi*), and the funnel structure at the inhalent end of an *Arenicola*-like burrow (Caster, 1957; Henbest, 1960; Pogue & Parks, 1958). Barthel & Barth (1972) described conical, *Conostichus*-like structures from the Devonian of Bolivia. They interpreted these structures to be the funnel-shaped openings of *Arenicola*-like burrows. In some of the specimens from the Rock Lake Shale, small rodlike structures can be seen on the apical end, with matching structures on the broader, opposite end (Pl. 5, fig. 1a,b). This suggested at first that the "rods" might be burrows extending through the structure and of possible *Arenicola*-funnel origin. However, cross sections did not reveal the existence of a well-defined, vertical burrow inside the trace, and an *Arenicola* origin could not be proved (Pl. 6, fig. 1b,c). The "rods" common at both ends are probably artifacts produced by the animal as it migrated up through the sediment.

Occurrence.—Rock Lake Shale Member (Loc. 4b).

Ichnogenus CRUZIANA d'Orbigny, 1842

Plate 5, figure 1

Type species.—*C. furcifera* d'Orbigny (1842, p. 30), subsequent designation by Seilacher (1953b, p. 107).

Description.—Small bilobed structure approximately 9 mm wide and 31 mm long, preserved in convex hyporelief. Surface of each lobe has numerous, straight ridges spaced less than 1 mm apart, oriented perpendicular to central groove.

Discussion.—Repichnia of small arthropod.

Cruziana is a bilobate trail with small, straight or curved ridges either perpendicular or at angles to a central furrow. This trace fossil is commonly thought to be the work of trilobites (Crimes, 1970; Seilacher, 1955, 1970; Birkenmajer & Bruton, 1971; Bergström, 1973). A trail similar to *Cruziana* is *Isopodichnus*. *Isopodichnus* is much smaller than *Cruziana* and is considered to have been made by other types of arthropods than trilobites (see discussion of *Isopodichnus*). According to Seilacher (1970, p. 456), small trails are very difficult to study and to interpret since the preservation of scratch marks is a fairly rare phenomenon. According to Seilacher (1970, p. 456), there are "no sound morphological criteria, except size, by which to distinguish *Isopodichnus* from *Cruziana*. Based upon this, it can prove difficult to distinguish small *Cruziana* from large *Isopodichnus*, as can be seen with the specimen in Plate 5, figure 1. If this specimen is compared with specimens of *Isopodichnus* from the Rock

Lake Shale, it is larger than all of them. Most specimens of *Isopodichnus* are only a millimeter or so wide.

Two major classes of arthropod trace fossils exist in the Rock Lake Shale. One group is represented by *Isopodichnus*, in the millimeter size class, the other is represented by forms about 10 mm wide. The latter group is represented by only two examples, the specimen described here and Arthropod trail A. In addition, these structures display well-defined sculpturing or scratch marks, which most of the small forms do not. Because of these differences in size and sculpture, the larger forms are considered to represent small *Cruziana*, at least in the Rock Lake Shale.

Bromley & Asgaard (1972, fig. 2) described a small specimen of *Cruziana* from Triassic freshwater deposits in East Greenland, which is identical in size and appearance to the material figured here. They considered that forms similar to their Greenland material have been described in Triassic freshwater deposits in Germany as *Isopodichnus* by Seilacher (1953b, 1960, 1963). Bromley & Asgaard (and references cited by them) argued that the material they described was probably made by notostracan branchiopods. It is possible that the Rock Lake Shale specimens may have a similar origin.

Freshwater, "Cruziana-type," trace fossils are also known from Carboniferous deposits in Bolivia (Helwig, 1972, fig. 9). Helwig's material is much larger than that figured here and by Bromley & Asgaard. There is no reason not to believe that large, freshwater arthropods might have been responsible for some of the *Cruziana*-like trails found in the fossil record. This may be especially true in paralic, upper Paleozoic sediments where true trilobite trails can still be found and potential confusion might result.

Occurrence.—Rock Lake Shale Member (Loc. 3).

Ichnogenus CURVOLITHUS Fritsch, 1908

Plate 2, figures 2a,b

Type species.—*C. multiplex* Fritsch (1908, p. 13), subsequent designation by Häntzschel (1962, p. W189).

Description.—Straight to sinuous structure with a trilobate surface, preserved in convex hyporelief or convex epirelief. Four to 6 mm wide, and 8 to 30 millimeters long. Bandlike, subelliptical in cross section, long axis parallel to bedding. Central lobe is 1 to 2 mm wide depending upon width of entire trace. In smaller specimens, central lobe proportionally smaller to total width of trail than in larger ones.

Discussion.—Repichnia of a mollusc, probably a gastropod.

Seilacher (1955, fig. 5-45) and Kiej (1965, fig. 2-6) figured specimens that closely resemble structures described here. Unlike their specimens, the poorly preserved epichnia of the Rock Lake Shale are not divided

into 3 lobes. Chamberlain (1971a, fig. 4N) described *Curvolithus* with a smooth, rounded lower surface and an essentially trilobate upper surface. Heinberg (1970, fig. 3a,b) illustrated two forms of *Curvolithus*. His "form one" possesses a trilobate upper surface (epichnia). The upper surface of his "form two" is similar to that of his "form one" except there is a thin medial groove on the central lobe. The bottom of both forms (hypichnia) display a well-defined trough that maintains a position between two opposing lobes in the structure. Häntzschel & Reineck (1968, p. 22-23, pl. 16-3) described *Curvolithus*, but did not specify whether the structure was preserved in hyporelief or epirelief. Nor did Häntzschel (1974, p. W56) later make a distinction.

It is apparent that *Curvolithus* may have many minor variations in form while still maintaining its basic trilobate configuration. Many of these morphological differences are probably related more to preservation than to construction of the structure. It, therefore, does not appear necessary to name new species for the Rock Lake material, which, when compared to other members of the ichnofauna, is scarce.

Occurrence.—Rock Lake Shale Member (Loc. 2, 3, 4).

Ichnogenus DIDYMAULICHNUS Young, 1972

Plate 4, figure 3

Type species.—*Fraena lyelli* Rouault (1850, p. 731), original designation by Young (1972, p. 10).

Description.—Small, bilobate, straight to gently curved trail, preserved in convex hyporelief. Surface of lobes smooth to slightly undulating. Median furrow separates equal-sized lobes. Width of trail, 4 to 7 mm, and several tens of millimeters long. Structures rarely intersect each other. Only one specimen commonly preserved on the same slab.

Discussion.—Repichnia of a small mollusc, probably a gastropod. Many types of recent gastropods are known to possess musculature in their foot, capable of ditactal movement (Schäfer, 1972).

Small specimens of *Didymaulichnus* might be confused with the bilobed trail *Gyrochorte carbonaria* Schleicher, 1954, which is present in the Upper Carboniferous cyclothems of the Ruhr Basin of Germany. However, *G. carbonaria* is much smaller than most specimens of *Didymaulichnus* and is apparently composed of two circular, curving rods parallel to and in contact with each other (Seilacher, 1964b, fig. 6). Seilacher (1963, p. 83) did not consider *Gyrochorte carbonaria* to be a true *Gyrochorte*, which typically displays biserially plated lobes in convex hyporelief and bilobed grooves paralleling the lobes in concave epirelief (Weiss, 1940; Seilacher, 1955, fig. 2).

The synonymies and occurrences of *Didymaulichnus* have been discussed by Young (1972, p. 10) and Hakes

(in Häntzschel, 1975, p. W61). From these listings, it is concluded that *Didymaulichnus* can commonly be thought to indicate shallow water deposition. Glaessner (1949, p. 390) described bilobate molluscan trails from the Lower Cambrian of Australia which were considered similar to *Didymaulichnus* by Young and placed them in the *Cruziana* facies. Daily (1972) since decided that these Australian forms are not similar to *Didymaulichnus*.

Occurrence.—Rock Lake Shale Member (Loc. 2, 3, 4b), Stull Shale Member (Loc. 1, 4), and Tecumseh Shale (Loc. 4a).

Ichnogenus DIPLOCRATERION Torell, 1870

Plate 5, figures 3a,b

Type species.—*D. parallelum* Torell (1870, p. 13), subsequent designation by Richter (1926, p. 213).

Description.—Vertical U-tube with spreite developed between limbs of tube. Limbs of successive U-tubes are confluent. Diameter of tube from 4 to 7 mm; distance between limbs of tube 28 to 35 mm; width of spreite 2 to 10 mm.

Discussion.—Domichnia of a worm.

No complete specimens of *Diplocraterion* have been found, and taxonomic interpretations have been done, by necessity, by reconstructions. Occasionally, small vertical burrows are continuous through sandstone beds several centimeters thick. These vertical burrows occur individually as *Tigillites* or in pairs. Where a spreite can be found to connect two vertical burrows, they are interpreted to be *Diplocraterion*. The burrow in Plate 5, figure 3b, is from the Tecumseh Shale and is preserved in a bed of sandstone 5 centimeters thick. The upper bedding plane has well-developed symmetrical ripple marks. Because the sandstone is thin-bedded, the complete structure of the burrow is missing. The lamellae of the spreite are concave upward, and can then be related to a vertical U-tube with a protrusive spreite, in the sense of Goldring (1962, fig. 2; 1971, fig. 3). It is difficult to imagine these structures could be the result of any other process. Fleming (1973, fig. 1) used similar criteria to interpret the origin of "fossil-cuff-links" to be *Diplocraterion* in the Miocene of New Zealand.

Vertical U-tubes are better preserved in the South Bend Limestone (Pl. 5, fig. 3a). There, well-developed spreiten and the basal curvature of the burrows are easily found preserved in hyporelief. Only rarely can the limbs of the U-tube be traced from the bottom to the top of the same bed. This is probably related to bed thickness (several tens of centimeters) and physical reworking of the sediment, which is almost totally structureless. Funnel, commonly associated with *Diplocraterion* on upper bedding planes, were not found with any of these burrows (Westergård, 1931, pl. 4).

The preservation of vertical, spreite-bearing U-tubes has received considerable attention (Richter, 1926; Sei-

lacher, 1967; Osgood, 1970; Knox, 1973; Fürsich, 1974b, and references therein). Most recently, Fürsich discussed the synonyms of *Diplocraterion* and established five ichnospecies for this ichnogenus. According to him, all vertical U-shaped burrows possessing spreite belong in the ichnogenus *Diplocraterion*. Variations in spreite development were considered taxonomically unimportant at the ichnogenetic level.

Earlier, Knox (1973, p. 134, 135) distinguished between *Corophioides* and *Diplocraterion* by differences in the manner of spreite construction. The spreite of *Corophioides* was characterized as having been produced by the lateral displacement of successive, migrating U-tubes. *Diplocraterion* resulted from the vertical migration of successive U-tubes, having confluent, vertical limbs. Häntzschel (1975, p. W53, W62) accepted Knox's definition of the two ichnogenera and did not consider them to be synonyms. Later, Knox (in Fürsich, 1974b, p. 954) discovered intermediate or transitional forms of *Diplocraterion* and *Corophioides* from the Jurassic of England. Because of this, Fürsich (1974b, p. 954) felt that the two ichnogenera could no longer remain independent. *Corophioides* Smith, 1893, therefore became *D. polyupsilon* Smith, 1893. In specimens from the Tecumseh Shale and South Bend Limestone, spreite developments display typical *Diplocraterion* structure. The limbs of successive U-tubes were confluent and *Corophioides*-like spreiten have not been found. The distinction between the two ichnogenera is maintained here.

Occurrence.—South Bend Limestone Member (Loc. 1, 4) and Tecumseh Shale (Loc. 4a).

?Ichnogenus GYROCHORTE Heer, 1865

Plate 5, figure 4

Type species.—*G. cosmosa* Heer (1865), subsequent designation by Häntzschel (1962, p. W196).

Description.—Small, bilobed structure, approximately 3 mm wide, preserved in convex epirelief. Lobes separated by a median furrow and composed of irregular, biserially arranged "plates."

Discussion.—Repichnia of a small amphipod (Abel, 1935) or worm (Heinberg, 1973).

Nathorst (1881, pl. 1, fig. 1) pictured plaster casts of *Corophium* or traces (in convex ?hyporelief), very similar to the material described here. Abel (1935, p. 279) later refigured Nathorst's specimen and compared it with "Zöpfe" structures from the Middle Jurassic of Germany. Weiss (1941, p. 333) considered these "Zopfplatten" to belong to *Gyrochorte* Heer.

The trace fossil from the Rock Lake Shale could, possibly, be a poorly preserved *Gyrochorte* because it has been demonstrated that *Gyrochorte* typically possesses bilobed ridges in epirelief and parallel, smooth, bilobed grooves in hyporelief (Seilacher, 1955, fig. 2; Heinberg,

1973, fig. 3). This hypichnial parallelism is lacking in the Rock Lakes Shale material, and therefore the trace cannot be unquestionably assigned to the ichnogenus.

Occurrence.—Rock Lake Shale Member (Loc. 3).

Ichnogenus FUCUSOPSIS Palibin in Vassoevich, 1932

Plate 8, figures 2a,b

Type species.—*F. angulatus*, by monotypy.

Description.—Trace straight to curved, 3 to 7 mm in diameter, with sublongitudinal, threadlike ridges or sculpture, preserved in convex hyporelief.

Discussion.—Fodinichnia of infaunal organism (?worm). Ridgelike sculptures apparently reflect burrowing activities of producer (Seilacher, 1959).

Fucusopsis is a well-known facies-crossing trace fossil. It displays no bathymetric control and has been reported to range from the *Nereites* to *Cruziana* facies (Seilacher, 1959, 1964; Osgood, 1970).

Superficially, *Fucusopsis* may appear similar to *Halopoa* Torell and *Scoyenia* White; both these genera are unilobate burrows with external sculpture. The surface of *Halopoa* was described by Martinsson (1965, p. 221) to possess an imbricate or lycopodiaceous structure. Several of his figured specimens display small ridges that are developed somewhat longitudinally (Martinsson, 1965, fig. 2), but these ridges are not as delicately sculptured and are proportionally much shorter than those described here. *Scoyenia* White (1929, p. 115, pl. 5) has delicately sculptured ridges. However, the ridges are typically short and "lanceolate," thereby differing from the material described here. Müller (1969, fig. 3, 4) figured *Scoyenia gracilis* with finely sculptured ridges, some of which appear continuous over a large portion of the burrow. On this basis, his material differs from *Scoyenia* as originally described by White (1929) and is more similar to the specimens from the Tecumseh Shale.

It would seem that *Halopoa*, *Fucusopsis*, and *Scoyenia*, as described in the literature, can be easily separated by the shape and distribution of their external sculpture ridges. In poorly preserved specimens, such differentiation might prove difficult.

Occurrence.—Tecumseh Shale (Loc. 3a).

Ichnogenus ISOPODICHNUS Bornemann, 1889

Plate 6, figures 2a,b; Plate 7, figure 2

Type species.—*I. problematicus* Schindewolf (1928, p. 27), subsequent designation by Schindewolf (1928, p. 27).

Diagnosis.—Bilobate structures preserved in convex hyporelief (1.2 to 2.8 mm wide and approximately 7 to 30 mm long), possessing a well-developed central groove that divides them lengthwise in two halves. Straight to gently curved. In the larger specimens, the surface of each lobe is not smooth but commonly displays transverse

striations spaced approximately 0.5 mm apart. Smaller traces do not have these striations but an undulating surface.

Discussion.—*Isopodichnus* is generally thought to have been produced by small arthropods (repichnia). See also *Cruziana*. Polychaetes and gastropods also have received credit for making similar bilobate structures (Schindewolf, 1928; Birkenmajer & Bruton, 1971). It is most likely that *Isopodichnus* from the Rock Lake Shale was produced by small arthropods. Transverse ridges on the lobes of large *Isopodichnus* (a few millimeters wide) were undoubtedly the result of scratching with pointed appendages during locomotion. Smaller forms of *Isopodichnus* do not have well-displayed transverse striations, probably because the size of the scratch mark is fairly close to the grain size of the sediment. Therefore, the striations were not preserved. Seilacher (1970, p. 456) noticed a similar relationship with different size specimens of *Cruziana*. *Cruziana*, less than 2 cm wide, do not adequately show claw marks necessary for specific division.

Isopodichnus has been considered to encompass two different forms: a narrow, continuous or an intermittent double-banded trail and a coffee-bean-shaped structure (Müller, 1955, 1967; Glaessner, 1957; Seilacher, 1960, 1963; Häntzschel, 1975). In other cases, only the coffee bean-like shape has been considered to be a "true" *Isopodichnus*. Birkenmajer & Bruton (1971) called all coffee bean-like resting traces with irregularly spaced transverse wrinkles *Isopodichnus*. Osgood (1970, p. 303) considered short *Rusophycus*-like imprints of "non-trilobite origin" to be *Isopodichnus*.

No coffee bean-shaped or intermittent bands representing *Isopodichnus* were found in the Rock Lake Shale. All specimens were continuous double bands along bedding planes, indicating little vertical movement of the producers in the sediment during the creation of its trail. In some cases, bilobate furrows have been preserved in epirelief (Pl. 6, fig. 2b). Directly beneath these furrows, hyporelief, typical *Isopodichnus* are found.

Seilacher (1970, p. 456) considered *Isopodichnus* to be a facies indicator of nonmarine sandstone of Paleozoic and Mesozoic age. Linck (1942, p. 253) restricted the ichnogenus to brackish water. In the Rock Lake Shale, *Isopodichnus* has been found on the same siltstone lense as *Lingula* (Pl. 7, fig. 2), and is associated with *Lingula* burrows (*Lingulichnus*), starfish impressions (*Asteriacites*), and *Conostichus*.

Occurrence.—Rock Lake Shale Member (Loc. 2, 3, 4b).

Ichnogenus LINGULICHNUS Hakes, ichnogen. nov.

Type species.—*L. verticalis* Hakes, *ichnosp. nov.*

Holotype.—KUMIP 107,820.

Diagnosis.—Sediment-filled tubes with elliptical cross sections. Tubes oriented perpendicular or inclined to bedding.

LINGULICHNUS VERTICALIS Hakes, ichnosp. nov.

Figure 10; Plate 6, figure 5; Plate 7, figures 1a-c

Description.—Vertical to slightly inclined structure, with horizontal cross section similar to that of a flattened ellipse; ends of long axis of ellipse are commonly pointed, but may be slightly rounded; commonly 8 mm long and 3 mm wide and preserved in both hyporelief and epirelief; trace may be surrounded by several sets of sub-concentric ellipses extending for a few millimeters away from the structure; trace may also be found on upper surface of laterally compressed, calyx-like structure (12 mm long, 9 mm wide, 11 mm high), which has a sub-circular outline at the base.

Discussion.—Domichnia of a linguloid brachiopod.

Lingulichnus is most commonly found on the tops of beds, having the outline of a laterally compressed ellipse. Depending upon the thickness and type of sediment, a similar elliptical structure can be found below the epichnion in hyporelief. Cross sections of these structures reveal that both the epichnion and hypichnion are connected by a subcylindrical burrow which conforms in horizontal cross section to the surface structures. At first glance, it might be thought that such structures were the result of worm activity. The trace fossils *Skolithos*

and *Monocraterion* are small cylindrical structures oriented perpendicular to bedding, but the flattened elliptical outline of *Lingulichnus* does not conform to the circular cross-sectional outline of these vertical worm burrows. In addition, there is no evidence for lateral compaction of the sediment.

Bivalves are producers of vertical burrows (Reineck, 1958). Bivalves have one plane of symmetry that passes through the plane of commissure, and their burrows should reflect this symmetry. *Lingulichnus*, however, has two planes of symmetry which coincide with its long axis and short axis. Therefore, it is not likely that *Lingulichnus* originated by the action of infaunal bivalves.

An infaunal organism known to produce vertical or subvertical burrows is the inarticulate brachiopod, *Lingula* (Craig, 1952; Ager, 1963, fig. 7.3; Ferguson, 1963). Its shell has the necessary symmetry to produce the flattened, elliptical outline characteristic of *Lingulichnus*. According to Rudwick (1970) and Craig (1952), *Lingula* positions itself vertically to subvertically in the sediment. The pedicle extends below the shell in the underlying sediment creating a cylindrical to slightly conical impression (Fig. 10). The small calyx-like structure in Plate 7, figure 1b,c, possesses a circular hypichnion that could have been made by a protruding pedicle. The elliptical epichnion was apparently produced by the shell in Plate 7, figure 1a, and the calyx-like structure could therefore represent the deepest penetration of the animal in its burrow. *Lingula* commonly retreats to the bottom of its burrow with its valves closed for safety to survive inhospitable conditions. The cross section of the burrow has sharply pointed ends and this suggests that the valves were closed when it was made. Specimens of *Lingula* have been found in the Rock Lake Shale (Pl. 7, fig. 2, and Moore, 1966).

Other specimens of *Lingulichnus* have been found with more rounded ends. The shape of the burrow made by *Lingula* in its feeding position, with both valves separate, closely resembles the outlines of these traces (Rudwick, 1960). The concentric laminations around the central part of the burrow are interpreted as the result of the animal packing the walls of its burrow and enlarging it because of sediment that passively filtered in. Many of these burrows have been packed so thickly by the producer that the burrows are nearly circular in outline. These burrows are similar to cross sections of *Lingula* burrows (with the animal still in the burrow) exposed along bedding planes in the Triassic of France (Gall, 1971, pl. 27, fig. 2).

Thayer & Steele-Petrović (1975) described the burrowing technique of *Glottidia pyramidata* and suggested a similar process for *Lingula*. *Glottidia* burrows anteriorly into the sediment surface, eventually producing a U-tube as it establishes a pedicle down orientation. Thayer & Steele-Petrović, therefore, suggested that many U-shaped

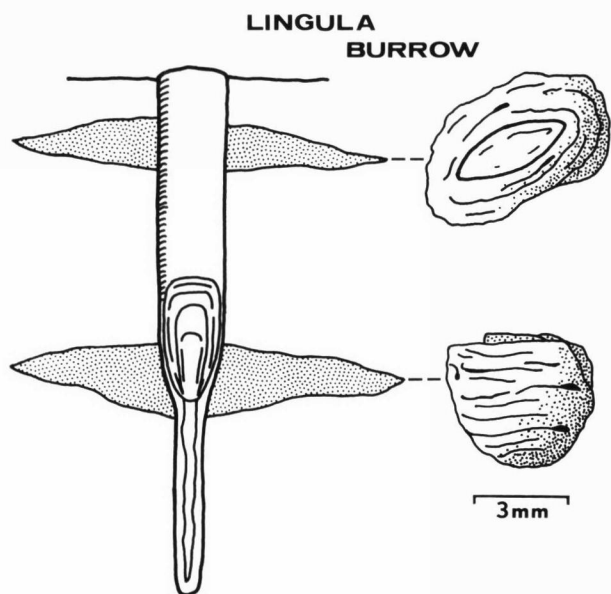


FIG. 10. Cross section of recent *Lingula* in its burrow, intersecting two silt lenses (after Rudwick, 1970). Figure in upper right shows epichnial expression of burrow; figure in lower right is side view of base of burrow with animal fully retreated. See also Plate 7, figure 1a-c.

burrows in the ancient record thought to have been produced by annelids may have been produced by lingulids. This could also be the case for some simple, vertical burrows. It should be possible, though, to demonstrate a lingulid origin for such burrows if the elliptical outline of *Lingulichnus* can be found within the burrow.

Occurrence.—Rock Lake Shale Member (Loc. 2, 3, 4b).

Ichnogenus LOCKEIA James, 1879

[=*Pelecypodichnus* Seilacher, 1955b, p. 105]

Plate 6, figure 3

Type species.—*L. siliquaria*, by monotypy.

Description.—Small, almond-shaped structures, preserved in convex hyporelief, and very rarely in concave epirelief. Dimensions range from 2 to 10 mm in length and 1 to 3 mm in width.

Discussion.—Commonly interpreted as cubichnia of bivalves (Seilacher, 1955b; Osgood, 1970; Eager, 1974), and some recently by conchostracan branchipods (Bromley & Asgaard, 1972). No conchostracan branchipods are known in the units studied, and they therefore are unlikely to have produced the material discussed below.

Moore & Merriam (1965) and Moore (1966) listed the bivalve fauna of the Rock Lake, Tecumseh, and Stull Shales. None of these genera are exclusively freshwater forms. The size of *Lockeia* suggests that small nuculids could be possible producers. Poorly preserved, small *Wilkingia* are also occasionally found. However, no bivalves are associated in the same bed with *Lockeia*, and it therefore is difficult to assign a definite producer to this trace fossil.

Lockeia has been found in shallow-water, marine sediments together with *Asteriacites* (Seilacher, 1955b). *Lockeia* (= *Pelecypodichnus* Seilacher) is also known to occur in nonmarine Upper Carboniferous deposits of Britain (Eager, 1974). These forms are preserved in concave epirelief together with the small bivalve *Carbonicola* on the same bedding plane.

Osgood (1970, p. 309) considered *Pelecypodichnus* Seilacher to be a subjective synonym of *Lockeia* James under the Law of Priority. Recently Eager (1974, fig. 8) rejected Osgood's decision because "James did not supply a figure with his original description." According to the International Code of Zoological Nomenclature (Art 12), to be available, type species established prior to 1931 need only to "have been accompanied by a description, definition, or indication" and James (1879, p. 17) did supply an adequate description of *Lockeia* in his original publication. The name *Lockeia* is maintained here.

Occurrence.—Rock Lake Shale Member (Loc. 1, 2, 3, 4b), Stull Shale Member (Loc. 5), and Tecumseh Shale (Loc. 1, 3, 4b).

Ichnogenus cf. LORENZINIA da Gabelli, 1900

Plate 6, figure 4

Type species.—*L. apenninica*, by monotypy.

Description.—Small subcircular structure consisting of 14 elongate, knoblike features (about 5 mm long) projecting from a raised central area (3 mm in diameter) with a subcentral pit. Preserved in convex epirelief. Diameter of entire structure approximately 4 mm.

Discussion.—There are many types of rosetted trace fossils. Recently their structure and supposed origins have been reviewed by Grubić (1970), and Häntzschel (1970) and many of them have been figured by Książkiewicz (1970, fig. 7).

It may prove that the specimen from the Rock Lake Shale is not a true *Lorenzinia*, which typically possesses a flat central area and is commonly much larger. *Lorenzinia perlata* Książkiewicz (1970, fig. 7p) is perhaps closest in appearance to the Rock Lake Shale material, but *L. perlata* has a flattened central area and is three to four times larger in diameter. *Bassaenia* Renz (1925) has some characteristics similar to this specimen. However, *Bassaenia* contains two concentric sets of small knobs and a flattened central area. Only one specimen of the Rock Lake Shale material has been found, and it is, therefore, only questionably assigned to *Lorenzinia*. Curiously, both *Lorenzinia* and *Bassaenia* are typical of flysch deposits (Häntzschel, 1975, p. W145).

It is possible these structures may have resulted from a small infaunal organism extending its siphon or other food-gathering organ into the overlying body of water. Such an origin would account for the raised central area, which could have been caused by mixing of sediment. The knobs might then be the result of movement of the food-gathering organ from the center of the burrow to its periphery.

Occurrence.—Rock Lake Shale Member (Loc. 3).

Ichnogenus MARGARITICHNUS Bandel, 1973

[*nom. subst.* for *Cylindrichnus* Bandel, 1967a, p. 6,
non *Cylindrichnus* Toots in Howard, 1966, p. 45]

Plate 8, figures 1a-c

Type species.—*Cylindrichnus reptilis* Bandel (1967a, p. 6), original designation.

Description.—Small, flattened, subspherical structures (up to 30 mm in diameter) preserved in convex epirelief and rarely, convex hyporelief. Structures can appear to be aligned in rows, straight to curved.

Discussion.—Domichnia of soft-bodied organisms, possibly anemone-like.

Bandel (1967a, p. 6) originally defined *Margaritichnus* under the name *Cylindrichnus* as "ball-like structures" . . . "commonly aligned like a string of pearls." Bandel interpreted these structures as fecal pellets, produced by

a large sediment-ingesting animal. A restudy of Bandel's material in the Museum of Invertebrate Paleontology at the University of Kansas furnished new information about the origin of these structures. On the fractured edges of sandstone blocks containing the trace fossil, some evidence of bioturbation could be found beneath some of the spherical bodies. This suggested a downward movement of the producer within the sediment, and downward movement of the producer is not in keeping with the original interpretation of a wormlike animal moving fairly horizontally in the sediment, leaving strings of fecal material behind.

Specimens of *Margaritichnus*, collected during this investigation, were found at two localities: 1) Bandel's locality (Killough quarry), and 2) at the Kansas Turnpike locality. *Margaritichnus* from the Kansas Turnpike was typically ball-shaped and much better preserved than Bandel's material. Many of the specimens from the Turnpike locality were arranged in strings (Pl. 8, fig. 1d), but it was not uncommon to find isolated specimens which were not aligned with others as if in a fecal string. In several instances, the ball-like structures were connected to similar structures on the opposite side of the rock by a cylindrical shaft with a diameter smaller than the balls (Pl. 8, fig. 1a). This definitely indicated vertical movement of the producer within the sediment.

Material collected from Killough Quarry showed short, stringlike arrangements of *Margaritichnus* (Pl. 8, fig. 1e) and, occasionally, a small ball could be seen inside a larger one (Pl. 8, fig. 1c). Sections were made of this material and saclike structures were found beneath what appeared to be balls of sediment on the surface (Pl. 8, fig. 1b). These saclike structures are reminiscent of anemones or anemone-like resting impressions as described by Shinn (1968) and Chamberlain (1971a). Unfortunately, permission could not be obtained to section the holotype for comparison. Sectioning of other material revealed little evidence.

Bandel (1967a, p. 6) compared his material with worm trails figured by Teichert (1941, p. 384, fig. 4) and assumed that his material had a similar origin. The shortest string of fecal pellets figured by Teichert has over twice the number of balls as the longest string figured by Bandel. It seems more likely that the strings of *Margaritichnus* from the South Bend Limestone formed by chance settlements of anemone-like organisms next to each other or in successive positions in the sediment. This explanation more clearly explains why many of the individual balls "impinge" upon each other (Bandel, 1967a, p. 6) and are even found inside each other. Variations of this trace fossil's morphology can best be related to lithology.

Occurrence.—South Bend Limestone Member (Loc. 4, 5).

Ichnogenus MICROSPHERICHNUS Hakes, ichnogen. nov.

Type species.—*M. linearis* Hakes, *ichnosp. nov.*

Holotype.—KUMIP 107,823.

Diagnosis.—Small ball-like structures in a linear arrangement. Balls may or may not be in contact.

MICROSPHERICHNUS LINEARIS Hakes, ichnosp. nov.

Plate 10, figures 1a,b

Description.—"Strings" of up to 10 or 12 tiny balls, approximately 1.4 mm in diameter, preserved in convex epirelief. Balls are irregularly spaced, every 5 to 7.5 mm.

Discussion.—Fecal balls produced endogenically by small worms during feeding (fodinichnia).

Bandel (1967a, p. 6) described somewhat similar structures from the South Bend Limestone, which he called *Margaritichnus* (Bandel, 1973, *nom. subst. pro Cylindrichnus* Bandel, 1967a, p. 6). However Bandel's specimens are much larger than *Microspherichnus*. In addition, balls of *Margaritichnus* may connect each other by a ridge the same width as the balls themselves. Some forms of *Taenidium* Heer, 1877, resemble *Microspherichnus*, but only superficially. *Taenidium* does not have the positive relief of *Microspherichnus*, and the balls in *Taenidium* typically touch each other and are slightly compressed (Häntzschel, 1972, fig. 3).

Neonereites uniserialis Seilacher, 1960, is also somewhat similar to *Microspherichnus*. *N. uniserialis* consists of strings of small balls in hyporelief. However, in epirelief, it is typically preserved as concave hollows, in a stringlike arrangement (Häntzschel, 1975). *N. uniserialis* as figured by Seilacher (1960, pl. 2, fig. 1) shows longitudinally compressed, subhemispherical hollows. Häntzschel & Reineck (1968, pl. 9, fig. 1, 2) figured specimens of *N. uniserialis* that were in part circular, hemispherical depressions. *Microspherichnus* is always preserved in convex epirelief and therefore differs in this respect from *Neonereites uniserialis*.

It is likely that the producer of *Microspherichnus* maintained a fixed depth within the sediment. Plate 12, fig. 1a shows the trace fossil intersecting a ripple crest whereupon the ball-like shape changes into a troughlike morphology. Once the producer of the trace left the ripple crest and migrated along the ripple slope (at a constant depth in the sediment) the ball-like structure was produced again.

Occurrence.—Rock Lake Shale Member (Loc. 3, 4b).

Ichnogenus NEONEREITES Seilacher, 1960

Plate 9, figures 1a-c

Type species.—*N. biserialis* Seilacher (1960, p. 48), by original designation.

Description.—Two closely spaced, straight to curved

rows of subcircular to crudely oblong knobs, preserved in convex hyporelief. Knobs of different rows are not opposite but alternate in position. Width of structure about 9 mm.

Discussion.—Fodinichnia of infaunal worms.

Seilacher & Meischner (1964, fig. 12) grouped the ichnogenera *Neonereites*, *Scalarituba*, and *Nereites* together, but not as strict synonyms. Differences in morphology were considered caused by different types of preservation. Chamberlain (1971a, p. 228) considered the three ichnogenera "probably" were synonyms and listed *Neonereites* and *Nereites* as forms of *Scalarituba*. Häntzschel (1975) separated these ichnogenera, and his view is accepted here. There is no doubt that bioturbate halos found to surround the *Scalarituba* burrow may be the result of lateral lobe development that has not been clearly preserved as suggested by Seilacher & Meischner (1964) (see *Nereites*). However, this variation in preservation of *Scalarituba* and *Nereites* yields a clear morphologic distinction between the two ichnogenera.

Seilacher & Meischner (1964) also explained the origin of the two alternating rows of knobs in *Neonereites biserialis* as the hypichnial expression of the lateral lobes of *Nereites* which are only found in epirelief. Width measurements of *Neonereites* and *Nereites* from the Tecumseh Shale show that the two are comparable in size. In cross section, *Nereites* has a disturbed zone beneath its central burrow (*Nereites*, Pl. 9, fig. 26). This zone would probably correspond to a *Neonereites* lump or knob if preserved in hyporelief. Unfortunately, single beds of the Tecumseh Shale are not sufficiently thin that epireliefs of *Nereites* show corresponding *Neonereites* patterns in hyporelief.

Cross sections through the *Neonereites biserialis* burrow reveal no indication of *Nereites*-type lateral lobes or a central burrow (Pl. 9, fig. 1b—arrows point to lobes). Indeed, cross stratification of the sediment is not disturbed by bioturbation. The *Neonereites* structures appear to have been produced within a sand layer slightly above the sand-clay interface. Subsequent wave action reworked the sand layer, destroying all evidence of the burrow except for two rows of depressions that were originally made in the underlying mud layer during lobe production. It is possible that a thin layer of sand (a few grains thick) adhered to the mud, thereby increasing the resistance of the mud to physical reworking. After initial consolidation, clays are not easily reworked by currents (Terwindt & Breusers, 1972, p. 87).

Although it is most likely that *Neonereites* and *Nereites* were produced by similar processes, this is no evidence to support the argument for specimens collected in the Tecumseh Shale. The two ichnogenera are therefore considered independent.

Neonereites is not bathymetrically controlled in Paleozoic sediments and has been reported from the *Nereites*,

Zoophycos, and *Cruziana* facies (Seilacher, 1964; written commun., 1975). In the Tecumseh Shale, it can be found in the same bed as *Diplocraterion*.

Occurrence.—Tecumseh Shale (Loc. 4a).

Ichnogenus NEREITES MacLeay, 1839

Plate 9, figures 1a-d

Type species.—*N. cambrensis*, subsequent designation by Häntzschel (1962, p. W205).

Description.—Smooth to slightly annulating central tube (2 to 8 mm wide) with lateral, subhemispherical lobes, preserved in convex epirelief. Width of entire structure up to 50 mm. Trace gently curved to sinuous. Not found to intersect each other.

Discussion.—Fodinichnia of worms.

Chamberlain (1971a, fig. 5) considered the lateral lobes to be an expression of periodic excavations by the producer along the walls of the central burrow. The sediment removed from the excavated lobes was back-filled behind the animal in the central burrow and also packed into empty lobes. This interpretation seems valid for the material described here. The annulating nature of the central burrow can be explained by this periodic back-filling. Several of the lateral lobes show evidence that they have been stuffed with sediment.

The morphology of *Nereites* is highly variable, and this variability is apparently caused by the relative position of the producer in the sediment with respect to the sand-mud interface. In all cases, *Nereites* is preserved in epirelief in sandstone. Three basic types can be recognized. Type 1 has a central burrow. The lateral lobes are nearly hemispherical and the points of intersection of neighboring lobes are very close to or are in contact with the central burrow (Pl. 9, fig. 2c). Type 2 has a central burrow. The lateral lobes are more irregular than those of Type 1 and the lobes show evidence of packing (Pl. 9, fig. 2a). The intersections of neighboring lobes are proportionally not as close to the central burrow as with Type 1 *Nereites*. Type 3 contains a slightly raised central ridge with poorly defined lateral lobes or mounds (Pl. 9, fig. 2d). All three types of *Nereites* are the result of the same basic behavioral pattern, the traces of which vary with the depth at which they were produced within the sand layer.

Nereites is commonly thought to be restricted to deep water and is the characteristic fossil of the *Nereites* facies (Seilacher, 1964b, 1967a,b, 1974; Seilacher & Meischner, 1964; Chamberlain, 1971a; Tanaka, 1971). In the Tecumseh Shale, *Nereites* is associated in the same bed with *Diplocraterion* and, stratigraphically, with *Tigillites*. In the Stull Shale, ?*Nereites* can be found within a few meters of a coal deposit. It is therefore very difficult not to consider *Nereites* as at least a restricted facies crossing form. Seilacher (1974a, fig. 2) discussed the tightly sinuous grazing pattern that developed in deep water

forms of *Nereites* by the end of the Paleozoic. This pattern is absent in the Tecumseh and Stull Shale specimens and might serve as a way to distinguish shallow water forms from deep water forms. However, Chamberlain (1971a,b) figured specimens of *Nereites* that do not have close meander systems from deep water deposits in the upper Paleozoic of the Ouachita System.

Occurrence.—Stull Shale Member (Loc. 5) and Tecumseh Shale (Loc. 1, 3, 4a).

Ichnogenus PLANOLITES Nicholson, 1873

Plate 10, figures 4a,b

Type species.—*P. vulgaris*, by original designation.

Description.—Unilobate or tubelike structures, irregularly intersecting the sediment surface. Preserved in convex hyporelief, concave epirelief (as troughs), and full relief. Up to 10 mm wide and several tens of millimeters long.

Discussion.—Fodinichnia of infaunal worms.

Planolites has become a catchall name for unilobate or tubelike burrows. Osgood (1970, p. 375) discussed the relationship of *Planolites* with the somewhat similar burrow *Palaeophycus* Hall (1847) and suggested that the two ichnogenera be carefully and extensively restudied in order to develop well-defined criteria for differentiating between them. Osgood quoted Nicholson (1873) and Nicholson & Hinde (1875) and tentatively distinguished between the two ichnogenera by comparing the lithologies of the burrow filling and the host rock. In *Planolites*, the sediment of the burrow filling is different from that of the host rock, suggesting active filling by the animal. In *Palaeophycus*, both lithologies are the same, suggesting passive burrow filling by inorganic processes. Possibly this criterion could ease any future taxonomic snarls. However, it is philosophically difficult and taxonomically confusing to differentiate between the two ichnogenera based upon the interpretation of the type of burrow filling. In practice, variations in lithologies from burrow to host rock might prove very difficult to use with any great deal of confidence and success, as already emphasized by Osgood (1970, p. 376). Burrows produced in thin-bedded sediments with alternating lithologies (i.e., fine-grained sandstone and clay) will be filled with mixed sediment of both lithologies. In addition, a change in deposition from sediment A to sediment B could cause passive infilling by sediment B of burrows previously produced in sediment A.

Frey & Chowns (1972) and Häntzschel (1975) considered the general morphology of *Palaeophycus* to be more variable than that of *Planolites*. *Planolites* is commonly a simple, cylindrical to subcylindrical burrow, while *Palaeophycus* may be sinuous, gently curved, and even branched. Until the two ichnogenera receive a detailed restudy, perhaps these last criteria may serve best.

Planolites is a known facies-crossing trace fossil. It

has been recorded from the *Skolithos* to the *Nereites* facies (Crimes, 1970, fig. 2). In the Upper Carboniferous cyclothems of the Ruhr Valley, two ichnospecies of *Planolites* have been considered facies dependent. Non-marine facies are represented by *P. montanus* Richter (1937) and marine to brackish conditions by *P. ophthalmoides* Jessen, 1950 (Seilacher, 1963). *P. montanus* is found in the Stull Shale. *P. ophthalmoides* has not been found in any of the units studied.

Occurrence.—Rock Lake Shale Member (Loc. 1, 3, 4b), South Bend Limestone Member (Loc. 3, 4, 5), Stull Shale Member (Loc. 1, 2a, 2b, 4, 5, 8), and Tecumseh Shale (Loc. 1, 3, 4a, 4b, 5, 6, 7b).

Ichnogenus RHIZOCORALLIUM Zenker, 1836

Plate 12, figure 5

Type species.—*R. jenense*, by monotypy.

Description.—Gently curved, protrusive, U-shaped burrows with spreite; vertical or oblique to bedding plane, or in bedding plane. Width of entire structure 55 mm and over 180 mm long. External tube or burrow poorly preserved and approximately 5 to 6 mm in diameter.

Discussion.—Domichnia of a suspension-feeding animal.

Rhizocorallium can display well-developed scratch marks, suggesting a crustacean producer (Weigelt, 1929; Seilacher, 1955; Fürsich, 1974a, p. 22). Such scratch marks are absent in the material described here. The preservation of the specimen in Plate 12, figure 5 is poor, and if scratch marks were produced, they have not been preserved. The absence of scratch marks may be a reflection of sediment grain size and coherency (Fürsich, 1974a, p. 22), as the coarser the sediment, the less likely the preservation of fine detail in the burrow walls. The lower part of South Bend Limestone is a calcite-cemented sandstone (Moore & Merriam, 1965).

Only two specimens of *Rhizocorallium* have been found, and they occur only along fracture surfaces. Their discovery was somewhat fortuitous, as surface expressions of the structures are difficult to observe. In both cases, the limbs of the U-tubes were parallel to each other, and the spreiten were obliquely protrusive.

Occurrence.—South Bend Limestone Member (Loc. 4).

Ichnogenus RUSOPHYCUS Hall, 1852

Plate 10, figure 5

Type species.—*R. clavatus* Hall (1852, p. 23), subsequent designation by S. A. Miller (1889, p. 138).

Description.—Smooth, bilobate, coffee bean-shaped structure, approximately 4 mm by 8 mm, preserved in convex hyporelief. Small raised ridge around margin of trace.

Discussion.—Cubichnia of a small arthropod. The

ridge around the trace is suggestive of the imprint of the doublure of a trilobite.

Only one specimen was found in the Rock Lake Shale, but other arthropod traces are associated with this specimen. *Rusophycus* has received extensive discussion, and it is generally accepted to be of trilobite origin (Seilacher, 1955, 1970; Lessertisseur, 1955; Osgood, 1970; Crimes, 1970). Many larger forms of the ichnogenus are known to possess series of scratch marks on their lobes. The size of the material described here is much smaller than "typical" specimens of *Rusophycus*, and therefore the possibility exists that some arthropod other than a trilobite was the producer. Seilacher (1970) claimed that the only difference between some forms of *Cruziana* and *Isopodichnus* was size (see *Cruziana*, and *Isopodichnus*). Large *Cruziana* are considered to be marine indicators and *Isopodichnus*, a freshwater indicator. A similar relationship may exist between large forms of *Rusophycus* and this much smaller one.

Occurrence.—Rock Lake Shale Member (Loc. 3).

Ichnogenus SCALARITUBA Weller, 1899

Plate 10, figure 3

Type species.—*S. missouriensis*, by monotypy.

Diagnosis.—Segmented, troughlike trace, 3.2 mm wide and about 20 mm long. Segmentation is the result of transverse partitions, spaced irregularly (2.4 mm to 3.8 mm). Trace has a slightly curved path. Transverse partitions are nearly parallel except where trace is curved, and then spacing between partitions is less on the inside of the arc than the outside. Likewise, the width of the partitions tends to be thinner on the inside of the curve. Preserved in concave epirelief.

Discussion.—This trace fossil is interpreted to be the result of a worm burrowing within the sediment and episodically back-filling the burrow, thereby creating the transverse partitions. Similar interpretations have been given by Seilacher & Meischner (1964), Conkin & Conkin (1968), Chamberlain (1971a), and Häntzschel (1975).

Only one specimen has been found in the Rock Lake Shale and it is not well preserved.

Seilacher & Meischner (1965, fig. 12) described the ichnogenus from the moderately deep, below wave-base *Zoophycos* facies of the Oslo region. It is also known from the *Zoophycos* facies of the Ouachita Mountains (Chamberlain, 1971b, fig. 6). Conkin & Conkin (1968, p. 1), on the other hand, considered *Scalarituba* to be indicative of tidal flat environments.

Occurrence.—Rock Lake Shale Member (Loc. 3).

Ichnogenus TIGILLITES Rouault, 1850

Plate 11, figure 1; Plate 13, figure 1

Type species.—*T. dufrenoyi* Rouault (1850, p. 741), subsequent designation by Häntzschel (1962, p. W218).

Description.—Small, vertical tubes between 5 to 10 mm in diameter. Length commonly less than 20 mm. Not closely packed. Cross sections of tubes visible in both epirelief and hyporelief. Preserved in full relief.

Discussion.—Domichnia of small worms.

These burrows are similar to *Skolithos* Haldemann, 1840, because of their tubular morphology and orientation with respect to bedding. However, they are much larger in diameter and are not as closely packed as *Skolithos* (Westergård, 1931; Howell, 1943; Hallam & Swett, 1966).

There is some question whether *Tigillites* and *Monocraterion* Torell, 1870, should be included under *Skolithos* Haldemann. This problem was discussed by Frey & Chowns (1972) and Häntzschel (1975), and there are no well-defined dividing lines between the three ichnogenes. All three consist of vertical tubes. *Monocraterion* always possesses a funnel at its upper end. *Tigillites* may possess a funnel which is absent in *Skolithos*. In funnel-less forms, the vertical burrows of *Skolithos* are commonly more closely packed than those of *Tigillites*. Frey & Chowns (1972, p. 26) differentiated between *Tigillites* and *Skolithos* by burrow diameter. *Tigillites* was interpreted to be the larger, and they did not consider burrow density to be taxonomically important.

Specimens of *Tigillites* from both the Tecumseh and Rock Lake Shales are preserved in thin-bedded sandstone and the entire burrow morphology cannot be accurately determined. Funnel-shaped structures have been found in float from the Rock Lake Shale, but none have been found to be directly associated with these vertical burrows. No U-tubes have been discovered in the Rock Lake Shale, and it seems likely that these funnels might be related to *Tigillites*. This, however, has not been proved. Because of the problem of preservation, the material described here is assigned to *Tigillites*.

Tigillites in the Tecumseh Shale is preserved in both physically and biogenically reworked sandstones. The specimens from the Rock Lake Shale are preserved in sediments that have not undergone noticeable reworking by either physical or biologic processes.

Occurrence.—Rock Lake Shale Member (Loc. 4b) and Tecumseh Shale (Loc. 4a).

?Ichnogenus TAENIDIUM Heer, 1877

Plate 11, figure 6

Type species.—*T. serpentinum* Heer (1877, p. 117), subsequent designation by Häntzschel (1962, p. W218).

Description.—Small, rodlike, unbranched structures (about 0.5 to 0.7 mm wide, and several tens of millimeters long) with well-developed transverse annulations, spaced 0.5 mm apart, preserved in convex epirelief.

Discussion.—Back-filled fodinichnia of infaunal worms.

The environmental range of similar back-filled bur-

rows has been reported from flysch facies (Heer, 1877; von Libernau, 1900) to nonmarine sediments (Seilacher, 1963; Toots, 1967; Stanley & Fagerstrom, 1974). The distribution of these burrows can certainly be considered facies independent.

There are two similar ichnogenera considered valid by Häntzschel (1975) with transverse annulations. They are *Keckia* Glocker, 1841, and *Taenidium* Heer, 1877. *Keckia* is much larger than *Taenidium* and the material described here. *Taenidium*, on the other hand, is more similar in size to the material described here but is commonly branched. Because the Rock Lake Shale specimens do not branch, they are tentatively assigned to *Taenidium*.

Occurrence.—Rock Lake Shale Member (Loc. 3, 4b).

Ichnogenus TEICHICHNUS Seilacher, 1955

Plate 11, figure 4

Type species.—*T. rectus*, by monotypy.

Description.—Bladelike spreite structures, 12 to 22 mm wide, over 0.1 m long, and approximately 50 mm high, wider at base than near top. Lamellae of spreite concave upward.

Discussion.—Fodinichnia of a wormlike animal.

No tube or burrow has been found within the spreite except in areas at which the burrow bends upward and intersects the bedding plane, where a circular burrow can be observed. The downward curvature of the spreite lamellae indicates that this and similar specimens of *Teichichnus* were retrusive. Broadening of the spreite at the base would probably indicate low rates of sedimentation, which allowed for some lateral migration of the animal within its burrows. The narrower upper portion might have resulted from a response to increased sedimentation wherein the inhabitant of the burrow moved rapidly upward in order to maintain a constant depth within the substrate. Under such conditions, the animal would have little time for lateral movements within its burrow.

These trace fossils are similar to burrows of the recent polychaete, *Nereis diversicolor*, as figured by Seilacher (1957, fig. 2). Martinsson (1965, p. 218) described large specimens of *Teichichnus* from the Cambrian of Sweden. The base of these structures displayed a noticeable bilateral symmetry which suggested to Martinsson an arthropod origin for them. Forms of *Teichichnus*, similar to those described here, are known from the Lower Carboniferous of Great Britain (Chisholm, 1970, pl. 8, fig. 2), and are preserved in sediment similar to that of the Stull Shale. However, none of the Stull Shale teichichnians possess scratch marks on their outer surfaces as do those described by Chisholm.

Occurrence.—Stull Shale Member (Loc. 5, 8).

Ichnogenus TOMACULUM Groom, 1902

[= *Synoprulus* Richter & Richter, 1939, p. 164]

Figure 11; Plate 11, figure 5

Type species.—*T. problematicum*, by monotypy.

Description.—Rod-shaped structures with somewhat rounded ends preserved in either concave epirelief or concave hyporelief. Length is from 1.5 to 2.2 mm and width from 0.3 to 0.5 mm. Most are straight, rarely curved, and may or may not be associated with a ?vertical, or subvertical burrow, 3 to 5 mm in diameter.

Discussion.—Molds of fecal pellets or coprolites.

There are many different types of coprolites mentioned in the literature (Häntzschel *et al.*, 1968). Probably the most extensively studied are those produced by crustaceans (Moore, 1933; Weimer & Hoyt, 1964; Bromley, 1967; Shinn, 1968). Many crustacean fecal pellets are rod-shaped. There is a distinct internal structure which is especially well displayed in the fecal pellets of the Anomura. This internal structure is taxonomically important and is thought to be valuable in the identification of probable producers (Brönnimann, 1972).

Since the material from the Rock Lake Shale is preserved as molds (concave epi- and hyporeliefs) and the coprolites and their internal structures have been removed by diagenetic processes, a definite crustacean origin cannot be proven, such as with *Favreina* Brönnimann, 1955.

Coprolites similar to those of the Rock Lake Shale have been described from the fossil record. The best known is *Tomaculum* Groom, 1902. *Tomaculum* is generally thought of as "strands" of "pellets" (Häntzschel, 1975, p. W143). Hofmann (1972, p. 194) reviewed the synonymy of *Tomaculum* and pointed out that Groom (1902, p. 127, 128) originally recognized as *Tomaculum* individual "sausage-shaped" or "egg-like bodies" and not strands of fecal pellets. If Groom's original definition is rigorously applied, any "sausage-shaped bodies" of appropriate size could be referred to *Tomaculum*, regardless of their arrangement.

Rod-shaped coprolites have been described from many different ages and have been found separately or associated with many different types of burrows. Chamberlain & Clark (1973) figured a discrete mound of supposed "protobrachiurid" spoil from the Upper Pennsylvanian of Utah, U.S.A. Goldring (1962, p. 240; 1971) found "compressed flat ended cylinders" associated with the trace fossil *Diplocraterion* in the Upper Devonian Baggy Beds of Great Britain. Coprolites have tentatively been referred to *Tomaculum* by Calver (1973, pl. 2, fig. 2) in the Westphalian of Great Britain. Similarly shaped fecal pellets are also known to be associated with *Diplocraterion* in the Jurassic of Great Britain and have questionably been attributed to crustaceans (Fürsich, 1974c, fig. 12c,d). Small, ellipsoidal pellets are known to be present inside the trace fossil *Quebecichnus* Hofmann, 1972, from the Lower Ordovician of Canada. Risk (1973, p. 1286) described the feeding traces of probable echiuroids and accumulations of fecal pellets from the Middle Thorold Sandstone in Canada. His specimens, too, closely resemble the material described here. The pellets are ap-

proximately 0.5 by 2 mm in size and are associated with a burrow 3 to 4 mm in diameter. Both the size of the pellets and the size and presence of the burrow conform well with the Rock Lake Shale material. According to Risk, echiuroids periodically expel quantities of fecal pellets from their burrows. These pellets accumulate at the mouth of the burrow on the sediment surface and can form cones up to 30 to 40 mm in height. However, grazing trails similar to those produced by recent echiuroids on the sediment around their burrow openings are absent from the Rock Lake Shale material. At this point the analogy breaks down.

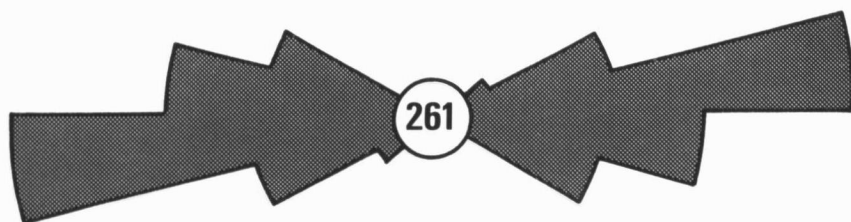
Orientation of coprolites.—The orientation of *Tomaculum* varies significantly within the Rock Lake Shale. At Locality 1, the northernmost outcrop (Fig. 4), the

coprolites fill ripple troughs and are aligned dominantly with their long axes parallel to each other and the surrounding ripple crests. Farther to the south, Locality 3 (Fig. 4), the same coprolites display no preferred orientation within the bedding plane.

Seilacher (1959, fig. 1; 1973) interpreted the first type of orientation as "wave orientation." Oscillatory wave movement aligns the elongate bodies so that their long axes are perpendicular to the direction of water movement and parallel to the ripple crests and to each other. Wave orientation has been described from the Upper Cretaceous of Texas where the conical foraminifer, *Haplostiche texana*, fills ripple troughs (Seilacher, 1960, fig. 7). Shells are not the only objects that can be wave-oriented. During low tide, along the beaches on the Georgia coast, it is

COPROLITE ORIENTATION

WAVE



BIOGENIC

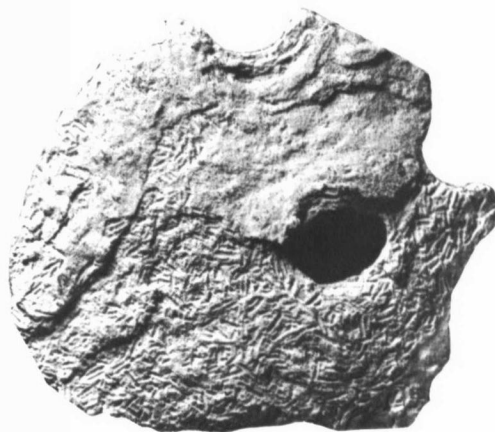
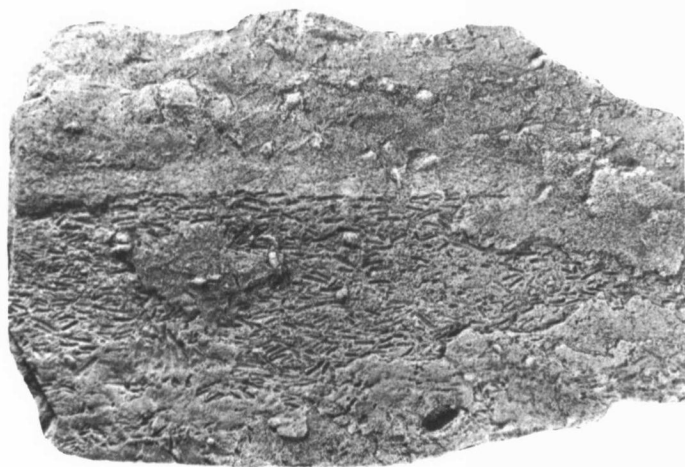
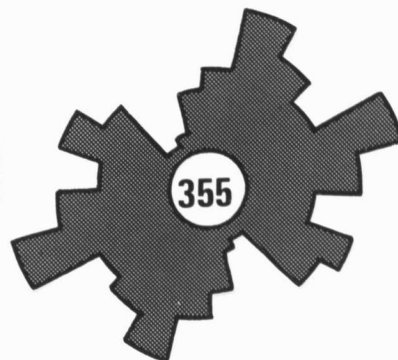


FIG. 11. Orientation of coprolites in the Rock Lake Shale. Left figure shows wave orientation, ripple trough filled with coprolites whose long axes parallel trough axis, preserved in concave epirelief; Loc. 1, 261 measurements of coprolite orientation in single trough, KUMIP 107,801. Right figure shows biogenic orientation, coprolites showing little preferred orientation within bedding plane. Loc. 3, 355 measurements, on single specimen, KUMIP 108,843 ($\times 1.4$).

common to find ripple troughs filled with the rod-shaped coprolites of the ghost shrimp, *Callianassa major* (John Warme, oral commun., 1975). This is apparently a situation analogous to the accumulation of coprolites in the Rock Lake Shale (Fig. 11). Current drifting of fecal pellets is a common phenomenon in the recent environment, and there is no reason not to find evidence for the removal of feces by currents in the fossil record. Some animals solve their sanitation problems by producing fecal pellets that can be carried away by currents. Animals unable to perform this feat would soon suffocate in or become infected by their own refuse (Schäfer, 1972).

At Locality 3, the more random orientation of coprolites suggests that they were not reworked by currents. In addition, circular burrows are commonly found associated with these coprolites (Fig. 11; Pl. 11, fig. 5). Since the coprolites associated with the burrows do not appear to be transported, it is possible that they were produced by the inhabitant of the burrow and dumped at the burrow's mouth. The rod-shaped coprolites of *Callianassa major* display similar orientation around the mouth of the burrow (Weimer & Hoyt, 1964, pl. 123, fig. 2). The significance of the orientation of biologic particles has been discussed in detail by Müller (in press).

It is not suggested that *Callianassa* is the probable producer of these coprolites (*Tomaculum*) in the Rock Lake Shale, but possibly a similar type of animal. The stratigraphic range of *Callianassa* does not extend back past the Mesozoic (Shimer & Shrock, 1944). However, *Thalassinoides*, a burrow commonly related to *Callianassa*, is known from Late Pennsylvanian sediments (Chamberlain & Baer, 1973). The shape of *Tomaculum* in the Rock Lake Shale and of recent callianassid fecal pellets are similar. Therefore, there is no reason not to expect to find *Tomaculum* similarly drifted and distributed.

Occurrence.—Rock Lake Shale Member (Loc. 1, 3).

?Ichnogenus TRICHICHNUS Frey, 1970

Plate 10, figure 2

Type species.—*T. linearis*, by original designation.

Description.—Fairly straight burrows less than 0.5 mm in diameter and over 50 mm long, preserved in convex epirelief. Burrows may cross each other and are oriented predominantly in a horizontal plane.

Discussion.—Combined dwelling-feeding burrow of a deposit feeder (Frey, 1970, p. 20).

Frey (1970, p. 20) originally defined *Trichichnus* to consist of "dominantly vertical, threadlike, cylindrical trichichnid burrows" with "distinct walls, commonly lined with diagenetic minerals." The material described here is dominantly horizontal, is not cylindrical but typically "halbform" and does not possess distinct walls, composed of diagenetic minerals. It has therefore been assigned only tentatively to *Trichichnus*. However, with

these differences in mind, striking similarities do exist. *Trichichnus* can be horizontal. Frey's specimens and the Rock Lake Shale forms are about the same size and develop along the same straight course. They do not possess well-defined constrictions or backfill structures, which suggests that they were not produced by sediment ingestion. A typical backfill burrow can be seen associated with ?*Trichichnus* in Plate 10, figure 2, for comparison. Apparently, ?*Trichichnus* was made by the displacement of sediment around the body of a very small organism.

Occurrence.—Rock Lake Shale Member (Loc. 4b).

MISCELLANEOUS BURROWS AND TRAILS

There are many different types of small, biogenic sedimentary structures, within the three units studied, that are not morphologically distinct or sufficiently abundant to warrant formal taxonomic treatment. Many of them are unique and do not resemble forms reported elsewhere and could well be assigned new ichnogeneric names. Based upon the material available, such action does not seem reasonable. If more of these forms are found in associated strata, then possibly a more formal treatment would prove necessary. However, it is important to describe them and to mention their relationships with other trace fossils.

ARTHROPOD TRAIL A

Plate 12, figure 3

Description.—Small, flat band (10 mm wide) with a rounded end, preserved in convex hyporelief. The surface of the trace is covered with a herringbone pattern of delicate, straight ridges that originate from both edges of the band, forming incomplete V's pointing toward the rounded end. The ridges are spaced approximately 0.6 to 0.7 mm apart.

Discussion.—Combination cubichnia and repichnia of a small arthropod. The direction of motion of the animal would be in a direction away from the rounded end.

Occurrence.—Rock Lake Shale Member (Loc. 3).

ARTHROPOD TRAIL B

Plate 12, figure 4

Description.—Small, gently curved, bandlike structure, approximately 5 mm wide and 24 mm long, preserved in convex hyporelief. Lateral margins possess small, converging ridges (1 to 1.5 mm long) spaced about 1 mm apart. Ridges surround a smooth central band and are oblique to margins of structure.

Discussion.—Repichnia of a small arthropod. Several specimens have been found; most are poorly preserved.

The small ridges on the margins of the trail do not extend across the smooth, central area. If extended, a herringbone pattern reminiscent of *Cruziana* results. The

V's of the herringbone would point opposite to the direction of locomotion (Seilacher, 1970). An arthropod transverse the sediment and digging relatively deep into the sediment with its appendages would produce a *Cruziana* structure if the entire underside of the bed were preserved. However, if the animal were to dig along the interface between mud and overlying silt and were to dig into the mud to such a depth that little of the overlying silt had mixed with the mud, a slurry would result with a poor potential for fossilization. The initial points of appendage penetration in the silt near the edges of the carapace margins would be the only distinctive feature. Such behavior would not necessarily mean that the animal burrowed within the sediment but could have burrowed at or near the sediment-water interface.

Variations in overall trace width and the length of scratch marks on the margins of the structure may also be explained by variations of the position of the animal's body with respect to the mud-silt interface and depth of penetration within the sediment. The initial points of penetration of the appendages at the interface would control the morphology of the scratch along the margins. The deeper the penetration, the wider the trace and the smaller the scratch marks. As the animal rose above the mud-silt interface, longer ridges or scratch marks would be preserved and the apparent width of the trail would decrease. The trail in Plate 12, figure 4, is interpreted to have been made by this process. The widest part of the trace is its central region where the ridges are smallest. This would correspond to the maximum burrowing penetration of the organism with respect to the mud-silt interface. At the upper end of the trace, the ridges are longer and the trail width has decreased, suggesting that the animal was increasing its distance from the interface. Seilacher (1970, fig. 4) has demonstrated that trilobites produce V-like scratch mark patterns from "tail down ploughing" through the sediment. In such a position, an arthropod could easily decrease its depth in the sediment.

Occurrence.—Rock Lake Shale Member (Loc. 2, 3).

BRANCHED BURROWS

Plate 13, figure 2

Description.—Small, branching structures about 1 to 2 mm wide and many millimeters long, commonly preserved in convex hyporelief. Each system commonly contains only one branching which may form an angle up to 90 degrees.

Discussion.—Fodinichnia of an infaunal organism.

These burrows are similar to *Chondrites*. However, they commonly display one bifurcation and not several as is more usually the case with *Chondrites* (Simpson, 1957).

Occurrence.—Rock Lake Shale Member (Loc. 2, 3, 4b) and Stull Shale Member (Loc. 5, 8).

CURVED BURROWS

Plate 11, figure 3

Description.—Small (approximately 3 mm in diameter), curved, cylindrical structures, preserved in both convex hyporelief and convex epirelief. Commonly, these structures lie within the bedding plane but can occasionally intersect the bedding from above or below. It is not uncommon to find these burrows will intersect each other.

Discussion.—Fodinichnia of small infaunal worms.

These trace fossils are found only at one locality in the Tecumseh Shale (Loc. 4a) and then in only one well-defined horizon.

Occurrence.—Tecumseh Shale (Loc. 4a).

GASTROPOD TRAIL

Plate 13, figure 4

Description.—Small troughs (10 to 20 mm wide) with raised margins, preserved in concave epirelief. Troughs may be gently to highly sinuous or may form crude circular paths. Margins are not rounded but appear to overlap the sediment surface.

Discussion.—Pascichnia of a gastropod on the sediment surface.

Many types of gastropods are known to produce trails similar to these along exposed areas of recent shorelines (Abel, 1935, fig. 176, 180, 181, 213; Baldwin, 1974, fig. 2).

Occurrence.—Tecumseh Shale (Loc. 1, 6).

LOOP BURROW

Plate 11, figures 2a,b

Description.—Small, circular, loop-shaped burrow preserved in convex hyporelief. The diameter of the loop is from 3.2 to 3.5 mm. Width of burrow is between 0.2 and 0.6 mm.

Discussion.—These loops represent the infaunal activity of small worms. The reason for this behavioral activity is not understood, but it is probably a feeding burrow (fodinichnia).

Two specimens have been found which are nearly the same overall size but have different burrow diameters. The larger burrow (Pl. 11, fig. 2a) has about the same burrow diameter as many of the small, nondescript burrows found in the Rock Lake Shale. Some of these burrows are curved and even partially sinusoidal. It may be possible that these loop burrows may in some way be related to *Cochlichnus*, also found in the Rock Lake Shale. Richter (1927, fig. 1c) illustrated a small, sinusoidal "free meander" produced in moist sand by the recent worm, *Eteona longa*. The burrow originates as a loop that changes quickly into a sinusoidal form. The burrow diameter is similar to that of the Rock Lake Shale specimen. However, the loop is open rather than closed.

Glaessner (1969, fig. 5F) figured a loop-like burrow from the Lower Cambrian of Australia that is similar to the Rock Lake specimen. Glaessner considered his material to belong to the *Cruziana* facies.

Incomplete loops, somewhat similar to those in Plate 11, figure 2b, have been described from the Nama Group of Southwest Africa (Germs, 1972, pl. 1, fig. 5). The diameter of the African specimen is approximately the same as that of the Rock Lake specimens, as is the burrow diameter. Germs considered these burrows to have been made in the *Cruziana* facies of Seilacher (1967).

Occurrence.—Rock Lake Shale Member (Loc. 3).

MEANDERING TRAIL

Plate 13, figure 5

Description.—Meandering trace, approximately 7 mm wide, preserved in convex epirelief. Lateral margins of structure display troughlike depressions. Meanders do not intersect.

Discussion.—Pascichnia of an infaunal ?worm.

Occurrence.—Stull Shale Member (Loc. 5, 8).

MOTTLED BURROWS

Plate 12, figure 2

Description.—Small, gently curved burrows several millimeters in diameter and several centimeters long. Burrows are close to each other and may intersect; they randomly intersect bedding planes. High burrow densities can completely destroy original depositional structures.

Discussion.—Fodinichnia of infaunal worms.

Two distinct burrow-mottled zones are found: 1) at the top of the Rock Lake Shale (Loc. 4a) and 2) at one distinct horizon within the Tecumseh Shale (Loc. 4a) near Lake Perry. In both cases, the mottling has local distribution. Generally, it is difficult to determine if intense bioturbation is the result of high infaunal abundance and activity, slow sedimentation rates, or a

combination of these factors (Middlemiss, 1962). The surrounding strata display abundant bioturbation structures, but to a lesser degree, it is probable that these bioturbation zones reflect periods of sedimentation that were lower than usual for both the Rock Lake and Tecumseh Shales.

Occurrence.—Rock Lake Shale Member (Loc. 4a, 4b) and Tecumseh Shale (Loc. 4a, 7a).

PLOWING TRAILS

Plate 13, figure 3

Description.—Small, approximately 10 mm wide, furrows with irregular, raised margins, preserved in concave epirelief.

Discussion.—Repichnia of small ?worms.

Very few of this type of trace fossil have been found. The irregular margins appear to reflect furrowing through the top layer of sediment by an organism.

Occurrence.—Rock Lake Shale Member (Loc. 1).

RESTING IMPRESSION

Plate 3, figure 1a; Plate 12, figure 1

Description.—Small, subhemispherical structures, up to 15 mm in diameter, preserved in convex hyporelief. Occasionally, corresponding depressions in epirelief can be found in very thin-bedded sediments.

Discussion.—Cubichnia of small, soft-bodied organisms.

These types of trace fossils are quite common in the Rock Lake Shale. In cross section, it is possible to observe that the structures are filled with sediment, which then has been covered by a thin layer of sediment (Pl. 12, fig. 1). Since this layer is continuous, it suggests that the producer of the trace fossil abandoned its resting place prior to the deposition of the upper layer.

Occurrence.—Rock Lake Shale Member (Loc. 3, 4b).

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APPENDIX

GEOGRAPHIC LOCATIONS OF MEASURED SECTIONS

LOCALITY		
NUMBER	TOWNSHIP AND RANGE	COUNTY
ROCK LAKE SHALE AND SOUTH BEND LIMESTONE		
1	SE¼ SW¼ sec. 30, T. 9 S., R. 23 E.	Leavenworth
2	SW¼ SW¼ sec. 1, T. 11 S., R. 22 E.	Leavenworth
3	NW¼ NW¼ sec. 8, T. 11 S., R. 23 E.	Wyandotte
4	SE¼ NW¼ sec. 18, T. 11 S., R. 23 E.	Wyandotte
5	NE¼ sec. 20, T. 13 S., R. 21 S.	Douglas
STULL SHALE		
1	SE¼ NW¼ sec. 24, T. 8 S., R. 21 E.	Jefferson
2	NW¼ SE¼ sec. 8, T. 11 S., R. 18 E.	Jefferson
3	SW¼ SW¼ sec. 13, T. 12 S., R. 18 E.	Douglas
4	NW¼ NW¼ sec. 24, T. 12 S., R. 18 E.	Douglas
5	SE¼ SW¼ sec. 13, T. 12 S., R. 18 E.	Douglas
6	SE¼ SE¼ sec. 13, T. 12 S., R. 18 E.	Douglas
7	SW¼ SE¼ sec. 18, T. 12 S., R. 19 E.	Douglas
8	SW¼ SW¼ sec. 26, T. 12 S., R. 18 E.	Douglas
TECUMSEH SHALE		
1	SE¼ NE¼ sec. 10, T. 10 S., R. 18 E.	Jefferson
2	SW¼ SW¼ sec. 11, T. 10 S., R. 18 E.	Jefferson
3	NW¼ NW¼ sec. 34, T. 11 S., R. 18 E.	Jefferson
4	SE¼ SE¼ sec. 3, T. 11 S., R. 18 E.	Jefferson
5	SE¼ SW¼ sec. 8, T. 11 S., R. 18 E.	Jefferson
6	NW¼ NW¼ sec. 17, T. 11 S., R. 18 E.	Jefferson
7	NW¼ NW¼ sec. 22, T. 12 S., R. 18 E.	Douglas

EXPLANATION OF PLATES

PLATE 1

FIGURE

1. *Asteriacites*.—1a. Convex hyporelief. Rock Lake Shale (Loc. 4), KUMIP 107,819, $\times 3.7$.—1b. Convex hyporelief. Numerous impressions; arm structure of producer visible in specimen in lower left. Rock Lake Shale (Loc. 3), KUMIP 107,830, $\times 2.7$.—1c. Concave epirelief; depression made by animal after leaving its resting place. Rock Lake Shale (Loc. 4), KUMIP 107,813, $\times 3.4$.
2. *Arenicolites*.—2a. Convex hyporelief. Limbs of U-tube protrude from bedding plane; basal curvature of U-tube missing. South Bend Limestone (Loc. 1), KUMIP 107,852, $\times 1.0$.—2b. Epirelief; tops of U-tubes at bottom margin of figure. Tecumseh Shale (Loc. 4), KUMIP 107,802, $\times 1.9$.—2c. Cross section of figure 2b showing U-tube. Tecumseh Shale (Loc. 4), KUMIP 107,802, $\times 1.9$.—2d. One limb of U-tube near basal curvature, in lower part of picture, displaying concentric packing of sediment around tube. South Bend Limestone (Loc. 1), KUMIP 107,852, $\times 1.4$.

PLATE 2

FIGURE

1. *Bergaueria*.—1a. Full relief; stereo pair, side view. Rock Lake Shale (Loc. 4), KUMIP 107,792, $\times 2.7$.—1b. Concave epirelief; stereo pair, depression in sediment beneath *Bergaueria* structure. Rock Lake Shale (Loc. 4), KUMIP 107,971, $\times 1.7$.—1c. Side view of figure 1d showing deformation of sediment beneath *Bergaueria*. Rock Lake Shale (Loc. 4), KUMIP 107,790, $\times 2.2$.—1d. Epirelief. Rock Lake Shale (Loc. 4), KUMIP 107,790, $\times 2.2$.
2. *Curvolithus*.—2a. Convex epirelief. Rock Lake Shale (Loc. 4), KUMIP 107,824, $\times 4.5$.—2b. Convex hyporelief. Rock Lake Shale (Loc. 4), KUMIP 107,804, $\times 2.7$.
3. *Aulichnites*.—Convex epirelief. Stull Shale (Loc. 8), KUMIP 107,842, $\times 0.9$.

PLATE 3

FIGURE

1. *Chevronichnus imbricatus* Hakes, *ichnogen. nov., ichnosp. nov.*.—1a. Concave epirelief; circular chevron trail originating from *Lockeia* in lower right; circular depressions are resting impressions. Rock Lake Shale (Loc. 4), KUMIP 107,822, $\times 2.3$.—1b. Concave epirelief; gently sinuous, crossing chevron trails without *Lockeia* at either end. Rock Lake Shale (Loc. 4), KUMIP 107,807, $\times 2.7$.

PLATE 4

FIGURE

1. *Chevronichnus* Hakes, *ichnogen. nov.*.—1a. Concave epirelief; gently curved trail, ending with *Lockeia* at left. Points of chevrons aim in direction of motion as suggested by shove marks in sediment to left of *Lockeia*; producer apparently moved from right to left. Rock Lake Shale (Loc. 3), KUMIP 107,876, $\times 4.5$.—1b. Recent *Cardium edule* transversing sediment, leaving a V-shaped path behind. Compare with figure 1a (Abel, 1935, fig. 217, by courtesy of Gustav Fischer Verlag, Stuttgart). Scale not given.
2. *Chondrites*.—2a. Convex epirelief; enlargement of right half of figure 2c showing numerous bifurcations. South Bend Limestone (Loc. 1), KUMIP 107,854, $\times 1.5$.—2b. Convex hyporelief; two sets of bifurcations. Rock Lake Shale (Loc. 4), KUMIP 107,815, $\times 2.9$.—2c. Convex epirelief; interrelationships of numerous *Chondrites* systems. Main shafts can be seen to curve upward into overlying sediment. South Bend Limestone (Loc. 1), KUMIP 107,854, $\times 0.7$.

3. *Didymaulichnus*.—Convex hyporelief. Rock Lake Shale (Loc. 4), KUMIP 107,834, $\times 2.0$.

PLATE 5

FIGURE

1. *Cruziana*.—Convex hyporelief; stereo pair, scratch marks well displayed. Rock Lake Shale (Loc. 3), KUMIP 107,829, $\times 2.3$.
2. *Conostichus*.—2a. Full relief; stereo pair, top view. Rock Lake Shale (Loc. 4), KUMIP 107,793, $\times 2.3$.—2b. Full relief; stereo pair, bottom view of specimen in figure 2a. Rock Lake Shale (Loc. 4), KUMIP 107,793, $\times 2.5$.
3. *Diplocraterion*.—3a. Hyporelief; bedding plane showing paired burrows with spreite between them. To right of hammer, paired *Arenicolites* tubes with sediment-packed walls (drawn from a photograph). South Bend Limestone (Loc. 1), $\times 0.2$.—3b. Concave epirelief; paired tubes with spreite. Tecumseh Shale (Loc. 4), KUMIP 107,849, $\times 1.4$.
4. *?Gyrochorte*.—Convex epirelief. Rock Lake Shale (Loc. 3), KUMIP 107,839, $\times 3.4$.
5. *Cochlichnus*.—Convex epirelief; sinusoidal burrow "originates" from circular structure at left. Two *Lockeia* are present in left and upper part of figure. Rock Lake Shale (Loc. 4), KUMIP 107,817, $\times 3.0$.

PLATE 6

FIGURE

1. *Conostichus*.—1a. Full relief; stereo pair, side view. Rock Lake Shale (Loc. 4), KUMIP 107,794, $\times 1.8$.—1b. Cross section; no burrow structure is evident below depression at center top. Rock Lake Shale (Loc. 4), KUMIP 107,796, $\times 2.5$.—1c. Cross section; structureless interior. Rock Lake Shale (Loc. 4), KUMIP 107,797, $\times 2.8$.
2. *Isopodichnus*.—2a. Convex hyporelief; shows relationship of large and small specimens of *Isopodichnus*. Rock Lake Shale (Loc. 3), KUMIP 107,848, $\times 2.9$.—2b. Concave epirelief; convex hyporelief, *Isopodichnus* below these grooves. Rock Lake Shale (Loc. 3), KUMIP 107,846, $\times 3.2$.
3. *Lockeia*.—Convex hyporelief. Rock Lake Shale (Loc. 4), KUMIP 107,824, $\times 1.6$.
4. Cf. *Lorenzina*.—Convex epirelief. Rock Lake Shale (Loc. 3), KUMIP 107,847, $\times 2.1$.
5. *Lingulichnus verticalis* Hakes, *ichnogen. nov., ichnosp. nov.*.—Convex epirelief; sediment packing around burrow. Rock Lake Shale (Loc. 3), KUMIP 107,835, $\times 2.7$.

PLATE 7

FIGURE

1. *Lingulichnus verticalis* Hakes, *ichnogen. nov., ichnosp. nov.*.—All specimens Rock Lake Shale (Loc. 4), KUMIP 107,820. —1a. Epirelief; stereo pair, $\times 3.6$.—1b. Full relief; stereo pair, side view, $\times 3.2$.—1c. Hyporelief; stereo pair, circular burrow in center, $\times 3.2$.
2. *Isopodichnus*.—Convex hyporelief; *Isopodichnus* developed on top of *Lingula* valve; *Lockeia* to left of *Lingula*. Rock Lake Shale (Loc. 3), KUMIP 107,832, $\times 3.6$.

PLATE 8

FIGURE

1. *Margaritichnus*.—1a. Cross sectional view; compressed balls on top and bottom of bed connected to each other by cylindrical shaft. South Bend Limestone (Loc. 4), KUMIP 107,806, $\times 1.4$.—1b. Cross sectional view; sac-like structures beneath balls on surface. South Bend Limestone (Loc. 5), KUMIP 107,798, $\times 1.4$.—1c. Convex hyporelief; ball inside ball in lower right hand corner. South Bend Limestone (Loc. 5), KUMIP 107,877,

×1.1.—1d. Convex hyporelief; balls arranged in curved path but do not touch. South Bend Limestone (Loc. 5), KUMIP 107,851, ×0.7.—1e. Convex hyporelief; balls touching each other in upper right corner. South Bend Limestone (Loc. 5), KUMIP 107,877, ×1.1.

2. *Fucusopsis*.—2a. Convex hyporelief; shows intersecting relationships. Circular burrows in upper right and middle left are *Tigillites*. Tecumseh Shale (Loc. 4), KUMIP 107,857, ×2.1.—2b. Convex hyporelief. Tecumseh Shale (Loc. 4), KUMIP 107,856, ×1.1.

PLATE 9

FIGURE

1. *Neonereites biserialis*.—1a. Convex hyporelief; sinuous course of *N. biserialis*. Tecumseh Shale (Loc. 4), KUMIP 107,860, ×0.9.—1b. Cross section; arrows point to two lobes of trace fossil. Cross bedding of sediment above lobes is undeformed by bioturbation. Tecumseh Shale (Loc. 4), KUMIP 107,858, ×4.5.—1c. Convex hyporelief; enlarged view of upper half of specimen in figure 1a. Tecumseh Shale (Loc. 4), KUMIP 107,860, ×2.3.
2. *Nereites*.—2a. Convex epirelief; packing of lateral lobes well displayed. Tecumseh Shale (Loc. 4), KUMIP 107,869, ×2.0.—2b. Cross section; central burrow with bioturbated lower margins, which form lateral lobes. Tecumseh Shale (Loc. 4), KUMIP 107,861, ×5.2.—2c. Convex epirelief; lateral lobes and central burrow well displayed. Trace fossil changes shape as it intersects ripple crest. Tecumseh Shale (Loc. 4), KUMIP 107,805, ×1.2.—2d. Convex hyporelief; poor definition and low relief of *Nereites* produced slightly below top of bedding plane. Tecumseh Shale (Loc. 3), KUMIP 107,867, ×2.2.

PLATE 10

FIGURE

1. *Microspherichnus linearis* Hakes, *ichnogen. nov.*, *ichnosp. nov.*—1a. Convex epirelief; balls disappear as trace fossil crosses crest of ripple mark in center of figure. Rock Lake Shale (Loc. 3), KUMIP 107,831, ×3.2.—1b. Convex epirelief. Rock Lake Shale (Loc. 4), KUMIP 107,823, ×3.2.
2. *?Trichichnus*.—Convex epirelief; larger *Planolites* burrow in upper left, arrow points to back-fill burrow, *?Taenidium*. Rock Lake Shale (Loc. 4), KUMIP 107,818, ×2.0.
3. *Scalarituba*.—Concave epirelief. Rock Lake Shale (Loc. 3), KUMIP 107,833, ×3.3.
4. *Planolites*.—4a. Convex hyporelief. Stull Shale (Loc. 5), KUMIP 107,873, ×3.0.—4b. Convex hyporelief. South Bend Limestone (Loc. 5), KUMIP 107,863, ×0.7.

5. *Rusophycus*.—Convex hyporelief; *Lockeia* in lower right corner. Rock Lake Shale (Loc. 3), KUMIP 107,836, ×4.9.

PLATE 11

FIGURE

1. *Tigillites*.—Epirelief; Rock Lake Shale (Loc. 4), KUMIP 107,814, ×2.3.
2. Loop burrow.—2a. Convex hyporelief. Rock Lake Shale (Loc. 3), KUMIP 107,828, ×4.5.—2b. Convex hyporelief. Rock Lake Shale (Loc. 3), KUMIP 107,838, ×4.8.
3. Curved burrows.—Convex hyporelief. Tecumseh Shale (Loc. 4), KUMIP 107,859, ×1.0.
4. *Teichichnus*.—Cross section perpendicular to burrow direction. Stull Shale (Loc. 8), KUMIP 107,810 & 107,811, ×1.8.
5. *Tomaculum*.—Concave epirelief; small burrow in upper left. Rock Lake Shale (Loc. 4), KUMIP 107,809, ×3.6.
6. *?Taenidium*.—Convex epirelief; morphology changes as burrow intersects ripple crest. Rock Lake Shale (Loc. 4), KUMIP 107,807, ×2.7.

PLATE 12

FIGURE

1. Resting impressions.—Cross section; overlying sediment is undeformed. Rock Lake Shale (Loc. 4), KUMIP 107,799, ×3.1.
2. Mottled burrows.—Side view. Tecumseh Shale (Loc. 4), KUMIP 107,800, ×2.0.
3. Arthropod trail A.—Convex hyporelief; small *Curvolithus* in lower right. Rock Lake Shale (Loc. 3), KUMIP 107,837, ×2.7.
4. Arthropod trail B.—Convex hyporelief. Rock Lake Shale (Loc. 3), KUMIP 107,845, ×3.9.
5. *Rhizocorallium*.—Full relief. South Bend Limestone (Loc. 4), KUMIP 107,827, ×0.9.

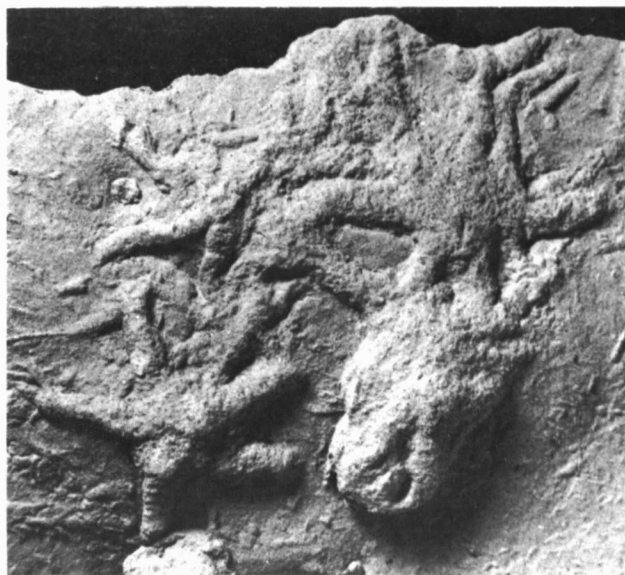
PLATE 13

FIGURE

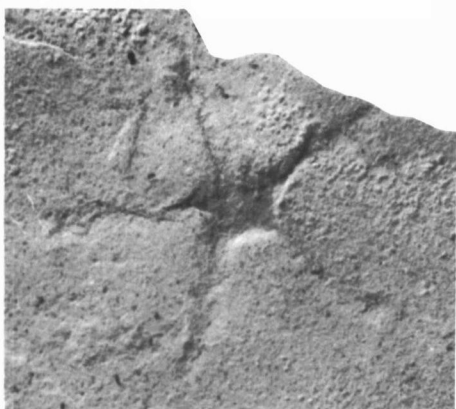
1. *Tigillites*.—Side view. Tecumseh Shale (Loc. 4), KUMIP 107,803, ×2.3.
2. Branched burrows.—Convex hyporelief. Stull Shale (Loc. 8), KUMIP 107,840, ×0.5.
3. Plowing trail.—Epirelief; dark flecks are plant fragments. Rock Lake Shale (Loc. 4), KUMIP 107,804, ×0.8.
4. Gastropod trail.—Small scale ripple marks in lower left. Tecumseh Shale (Loc. 6), KUMIP 107,880, ×1.2.
5. Meandering trail.—Convex epirelief. Stull Shale (Loc. 5), KUMIP 107,874, ×0.9.
6. Tool marks.—Convex hyporelief. Rock Lake Shale (Loc. 3), KUMIP 107,844, ×3.8.



1a



1b



1c



2a



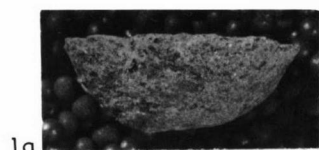
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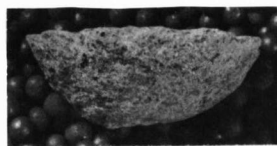
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1a



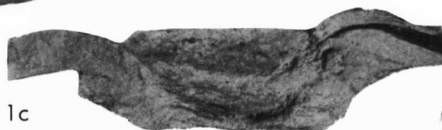
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3



2b

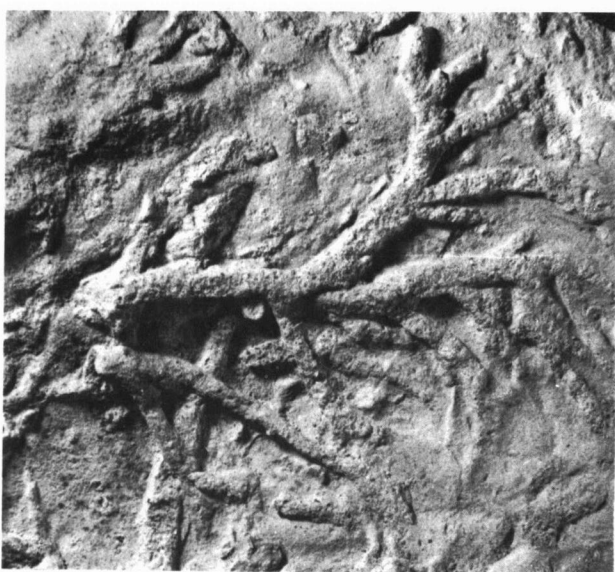




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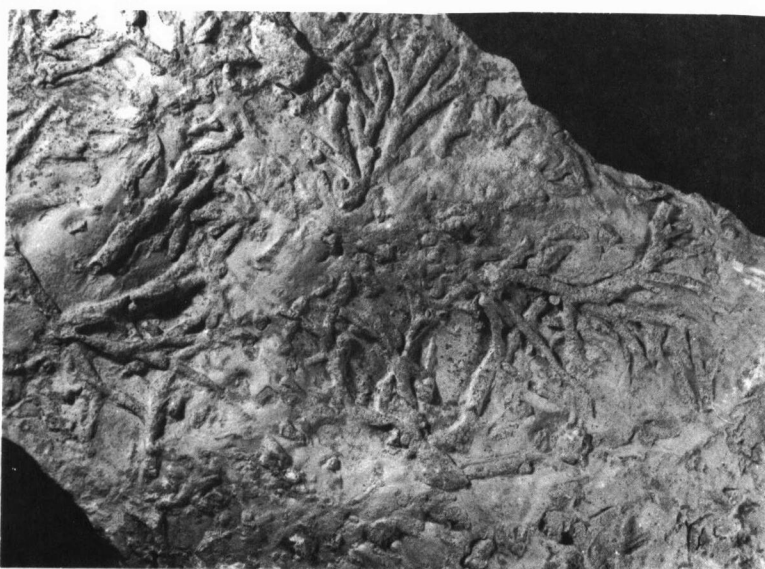
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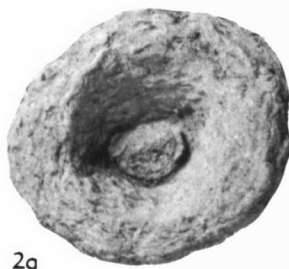
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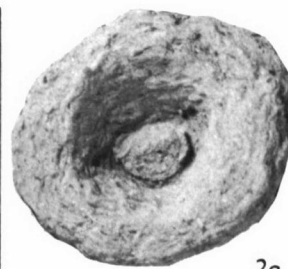
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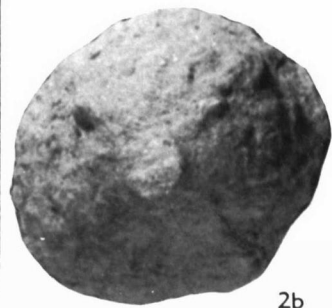
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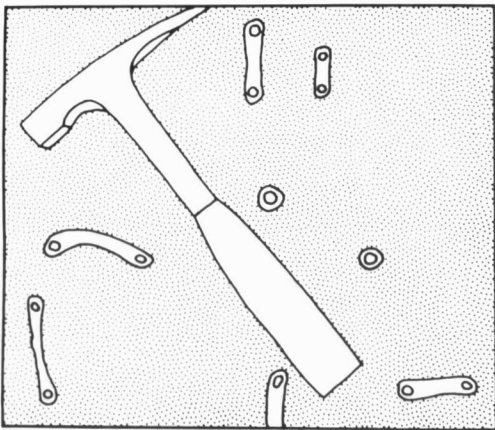
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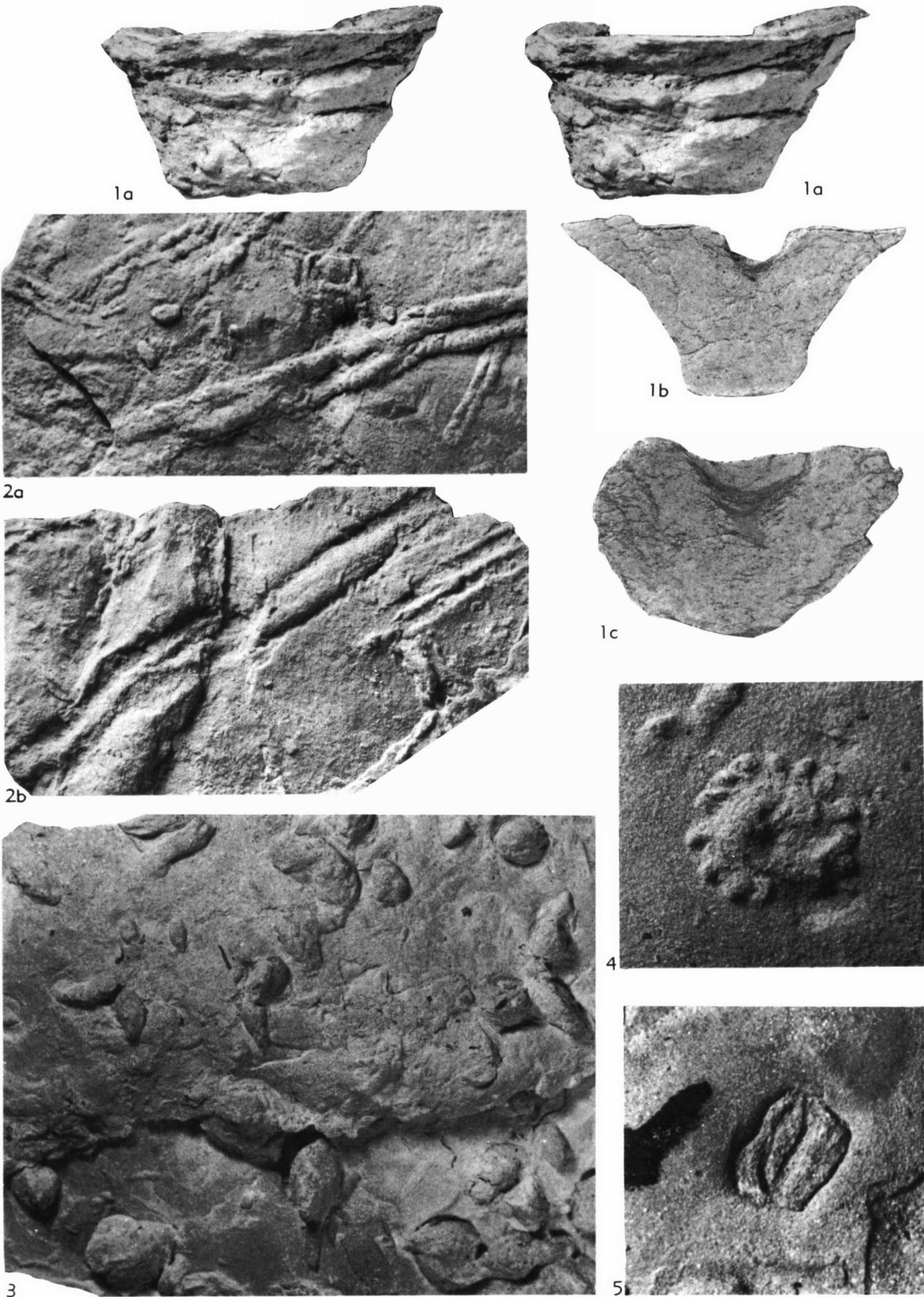
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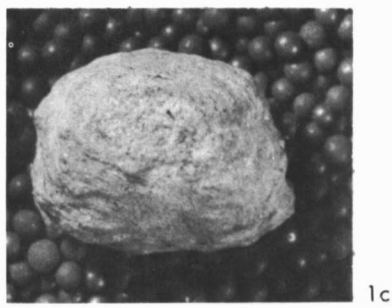
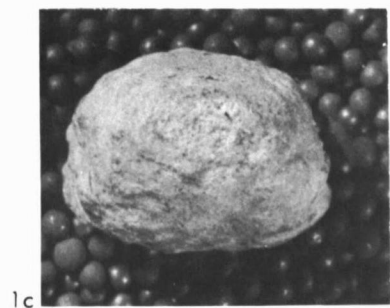
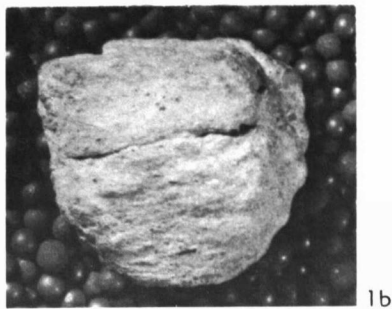
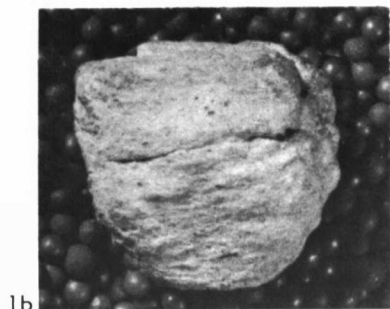
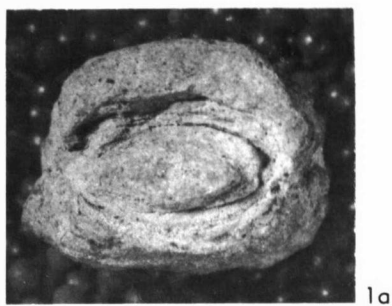
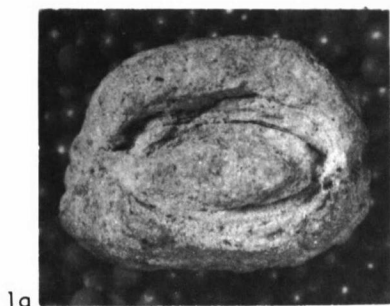


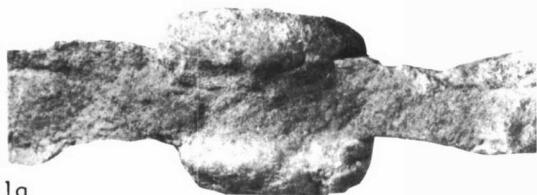
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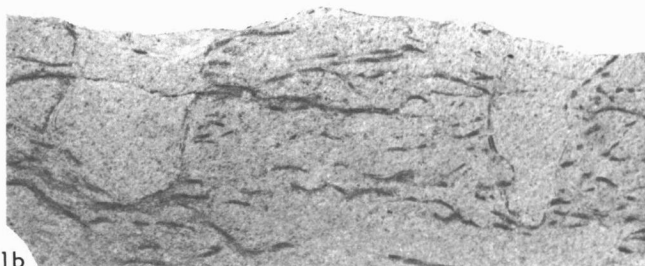
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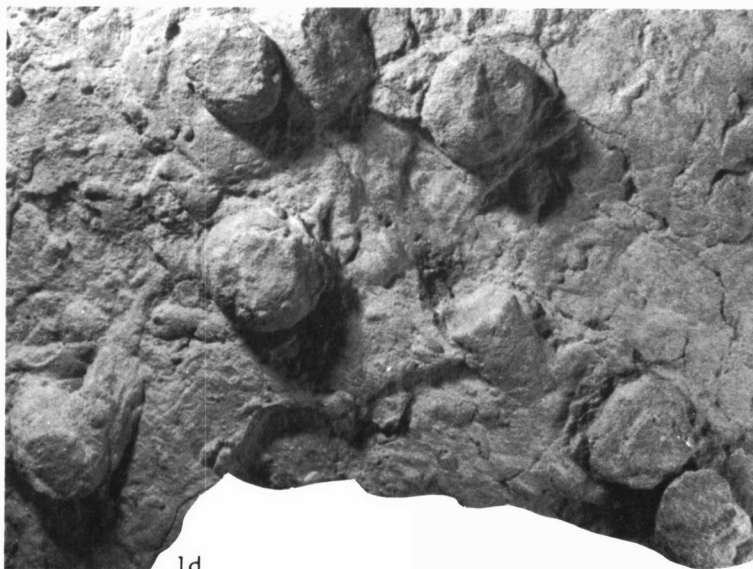
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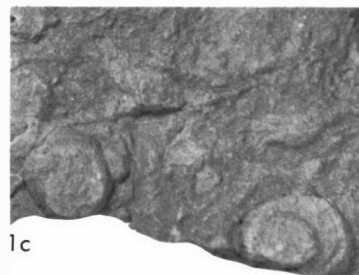
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1b



1d



1c



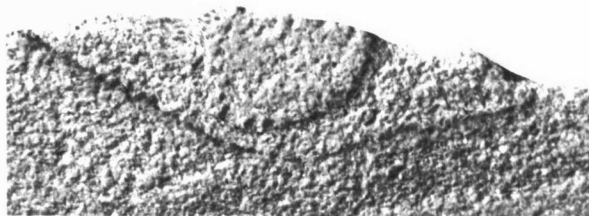
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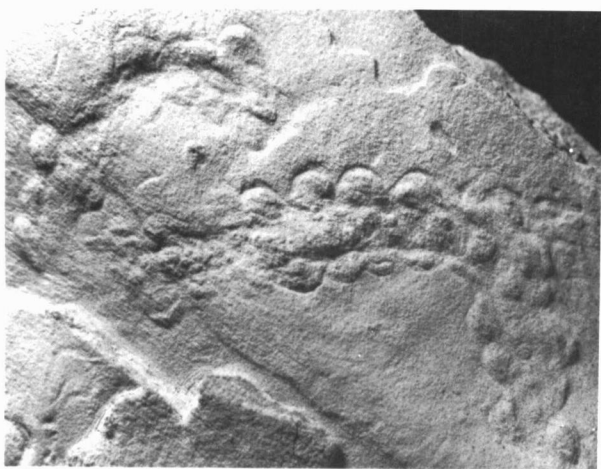
1a



2a



2b



2c



1b



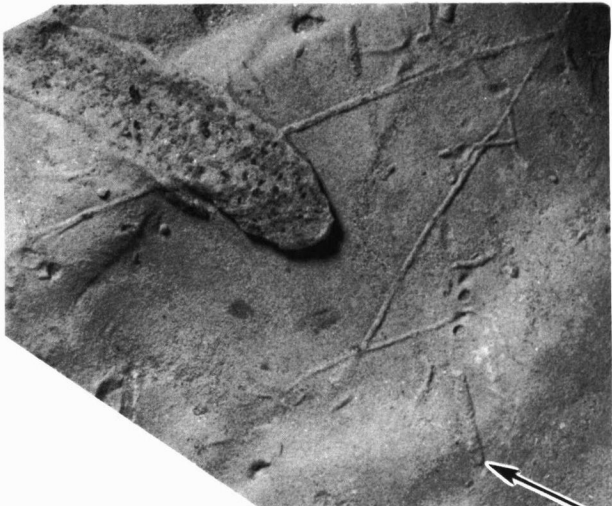
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1c



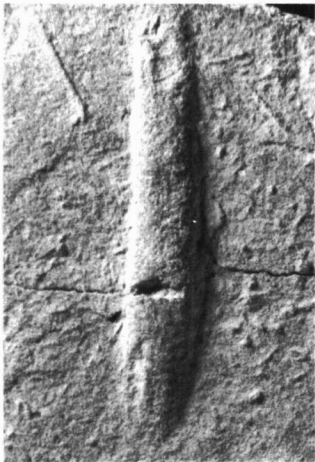
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2



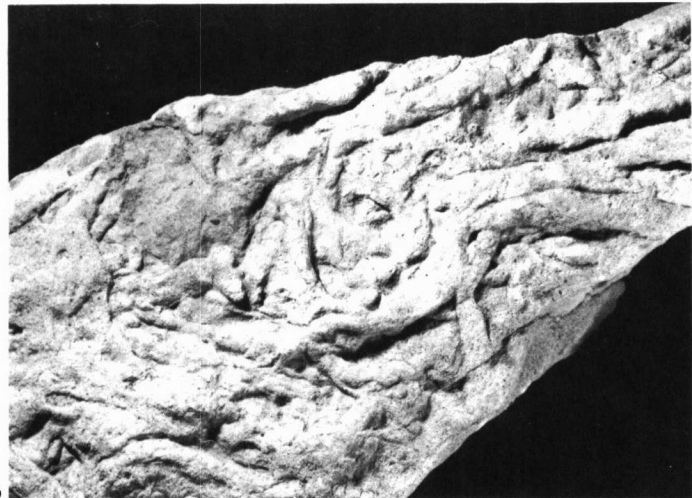
3



4a



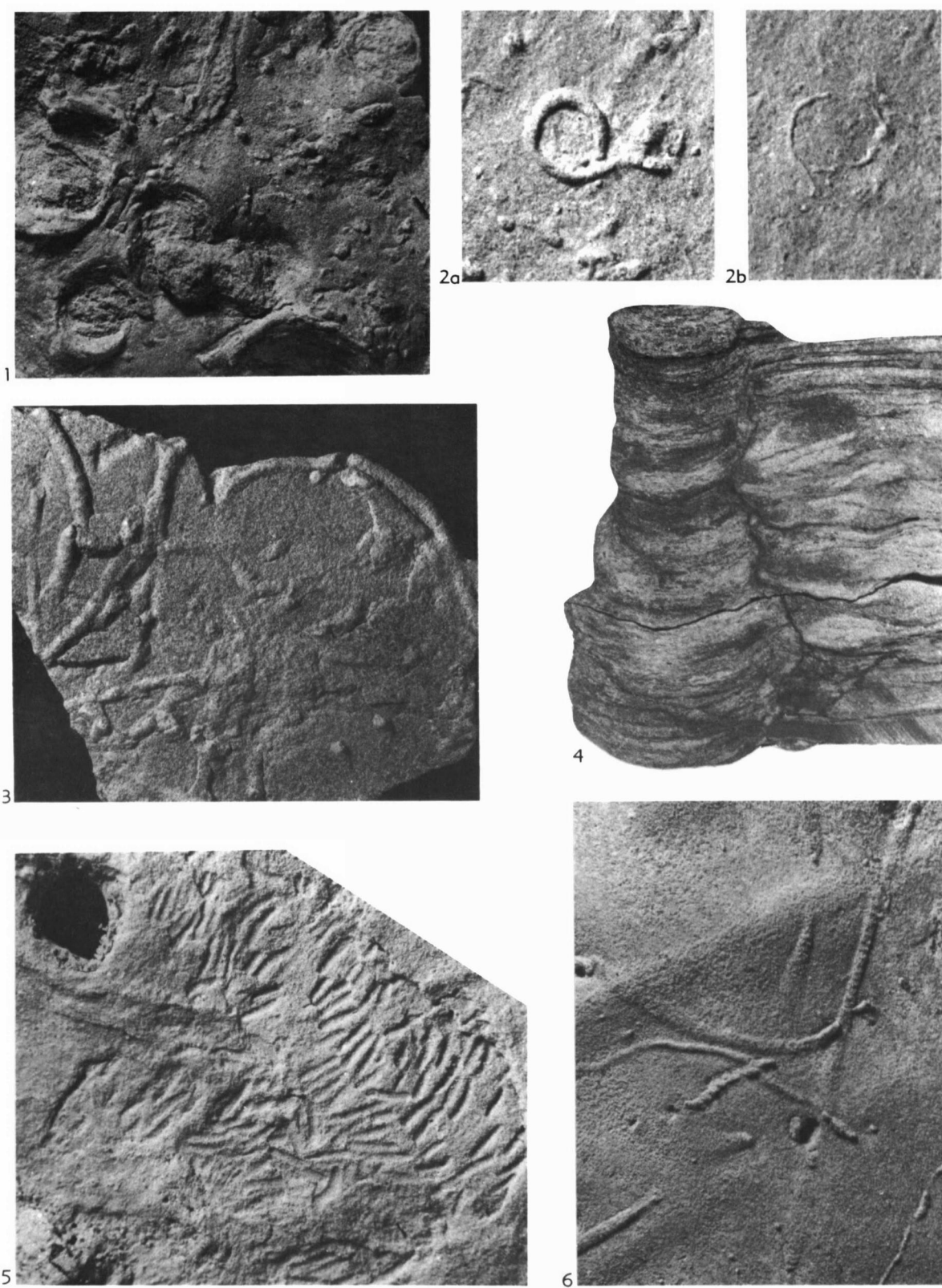
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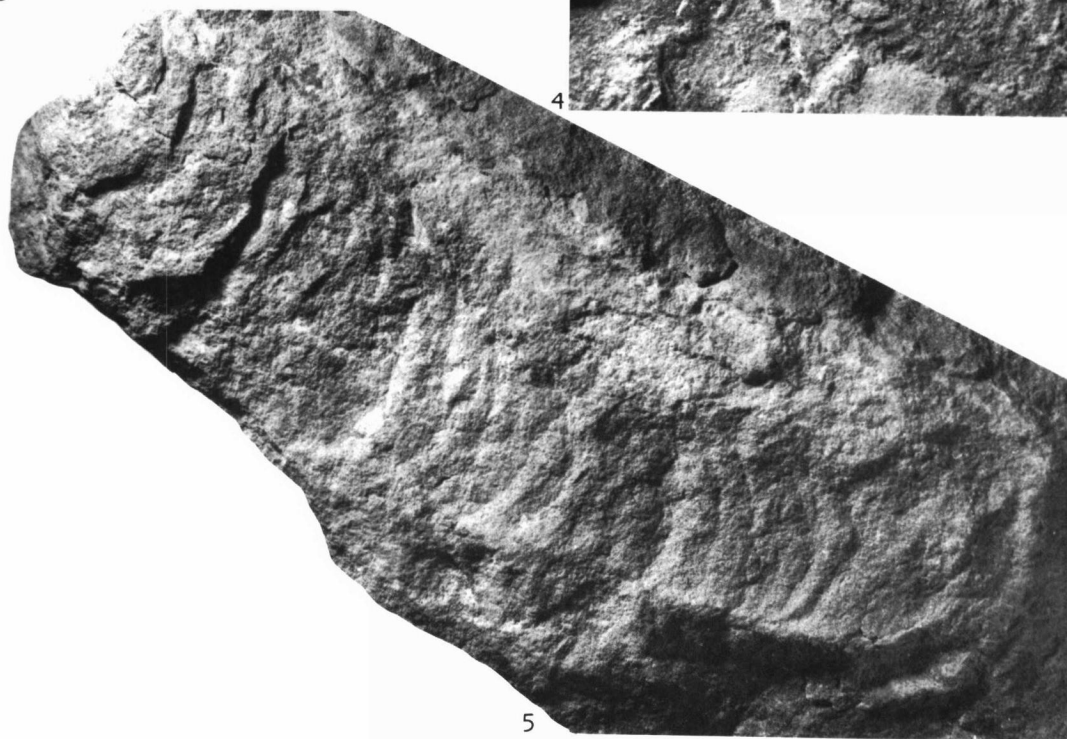
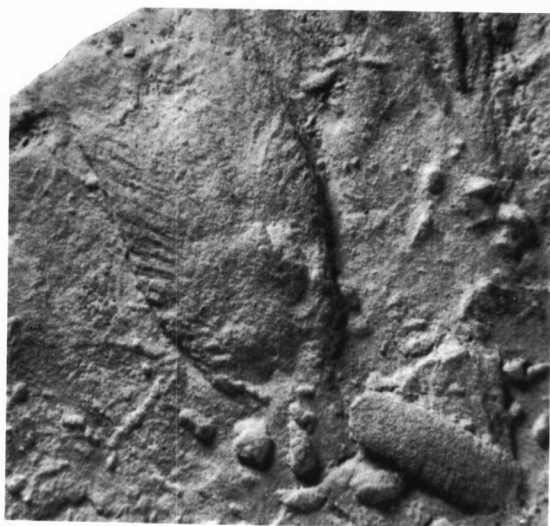
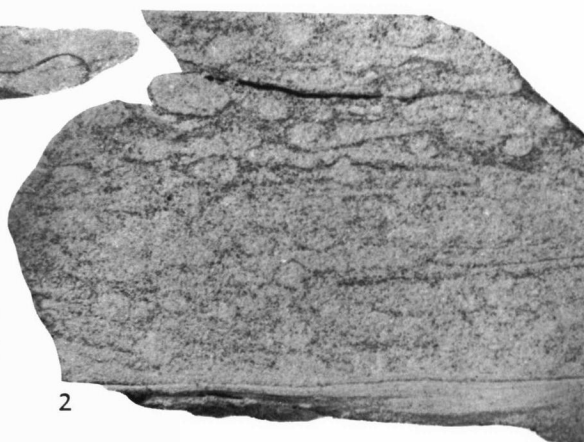
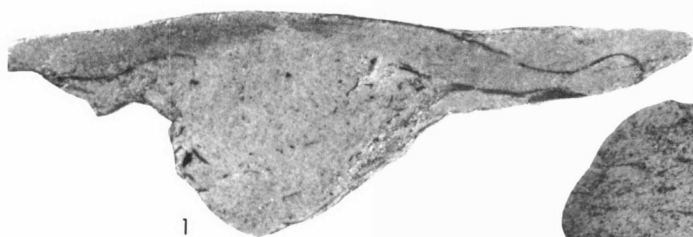


4b



5



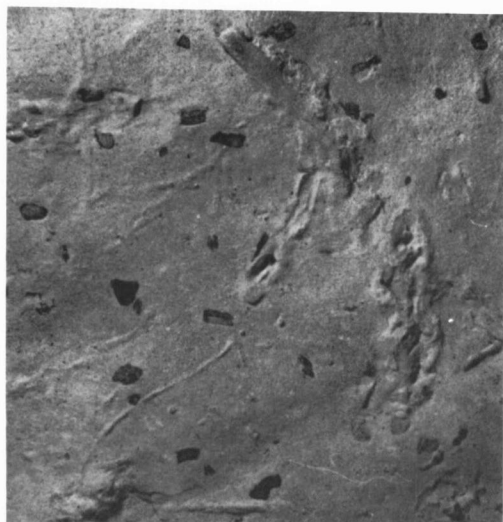




1



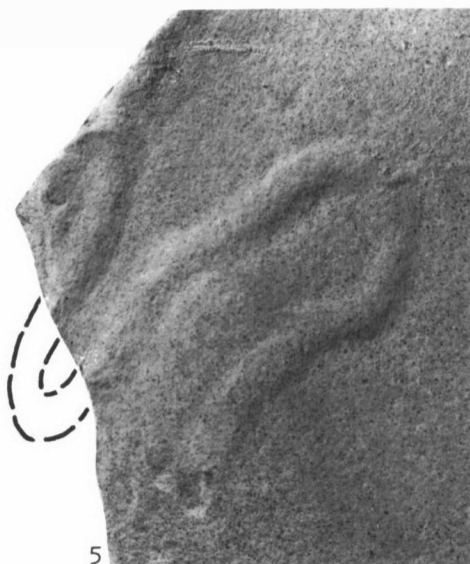
2



3



4



5



6

